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TROUGH CREEK LIMESTONE BARRIER INSTALLATION AND EVALUATION

AFRICA ENGINEERING ASSOCIATES,
INCORPORATED

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Six prototype crushed limestone barrier installations were constructed in Trough Creek in South Central Pennsylvania to demonstrate the neutralizing ability of this type structure in low-iron acidic streams.

Limestone barrier performance was excellent during periods of low streamflow, in terms of reducing acidity and raising the pH of the water, but their effectiveness was marginal at design or average streamflow, and they were ineffective when high runoffs were experienced. Limestone barrier performance deteriorates after the structures are initially constructed and placed in operation, because progressive accumulations of sediment clog interstices between the stones, which lessens the hydraulic conductivity of the barriers, and surfaces of the stones become coated with silt, which causes a reduction in reactivity of the reagent (limestone) with flowing acidic water. The design of limestone barriers should take these factors into account, and the units should be sized sufficiently large to overcome this deficiency.

Silted limestone barriers can be restored to porous filtering beds, approximately equal in performance to initial efficiency, by washing and rehandling the crushed limestone materials.

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May 1976

TROUGH CREEK LIMESTONE BARRIER

INSTALLATION AND EVALUATION

by

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the pollutional impact on our environment and even on our health often requires that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-CI) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

The Trough Creek Limestone Barrier Installation and Evaluation Project was undertaken to explore the feasibility of providing a low cost treatment method for abatement of pollution caused by acid mine drainage. This report summarizes the findings of a study on the performance of limestone barriers placed in a stream channel to effect neutralization of acidity. The work presented augments other types of mine drainage treatment studies performed by the Extraction Technology Branch which involve elaborate handling and pumping mechanisms. Results obtained here will especially benefit state and local agencies charged with clean-up of acid streams. The guidance presented in this report helps to define areas where limestone barriers are feasible and to outline their construction details. Although the use of limestone barriers is severly limited by stream quality and flow characteristics, the method is an effective alternative given the correct conditions.

David G. Stephan, Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

Six prototype crushed limestone barrier installations were constructed in Trough Creek in South Central Pennsylvania to demonstrate the neutralizing ability of this type structure in low-iron acidic streams. The project included a stream gaging and sampling program to evaluate the effectiveness of limestone barrier performance under actual stream conditions, and to assess the adequacy of design relationships developed from laboratory research.

Limestone barrier performance was excellent during periods of low streamflow, in terms of reducing acidity and raising the pH of the water, but their effectiveness was marginal at design or average streamflow, and they were ineffective when high runoffs were experienced. Limestone barrier performance deteriorates after the structures are initially constructed and placed in operation, because progressive accumulations of sediment clog interstices between the stones, which lessens the hydraulic conductivity of the barriers, and surfaces of the stones become coated with silt, which causes a reduction in reactivity of the reagent (limestone) with flowing acidic water. The design of limestone barriers should take these factors into account, and the units should be sized sufficiently large to overcome this deficiency.

Silted limestone barriers can be restored to porous filtering beds, approximately equal in performance to initial efficiency, by washing and rehandling the crushed limestone materials.

This report was submitted in fulfillment of Project Number 14010 FWW by the Commonwealth of Pennsylvania, Contract No. CR-105, and was prepared by Africa Engineering Associates, Inc., of Huntingdon, Pennsylvania 16652 under the partial sponsorship of the Environmental Protection Agency. The work was completed February 15, 1975.

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The support, guidance and assistance by the Environmental Protection Agency project officers were greatly appreciated.

SECTION I

CONCLUSIONS

Research in the late 1960's at The Pennsylvania State University indicated the feasibility of placing barriers of crushed limestone in streams to effect reduction of acidity, and it was recommended that limestone barrier neutralization should be demonstrated in selected prototypes.

Trough Creek, which is located in South Central Pennsylvania, was polluted with acid mine drainage in the upper reaches of the watershed. This stream was selected for prototype limestone barrier installations at six sites in the watershed because iron and sulfate concentrations of the water were low, except at one location where the iron concentrations were in the neighborhood of 30 mg/l.

Alternate schemes for channelling stream flow, along with different structural configurations and barrier shapes, were incorporated in the design at the various installations so that an assesment could be made under actual stream conditions of the most effective type limestone barrier for reducing the mineral acidity of the water.

During the course of the sampling and analysis portion of the Project, severe flooding (Tropical Storm Agnes in 1972) was experienced in the watershed causing damage to completed limestone barriers. Selected barriers were reconditioned, repaired, and restored to approximate original condition.

The sampling and analysis program was authorized to evaluate the performance of the limestone barriers under actual stream conditions, and to determine the adequacy of design relationships developed from laboratory research. An evaluation of the performance of the Trough Creek Limestone Barriers, based on results of the sampling program and observations noted in the field, indicates the following:

1. Neutralization of stream acidity can be accomplished by placement of limestone barriers in a stream channel.

2. Limestone barrier performance for the Trough Creek Project did not meet theoretical efficiency.

3. Although barrier performance was excellent during periods of low stream flow, in terms of reducing acidity and raising the pH of the water, their effectiveness was marginal at average stream flow, and they were completely ineffective during periods of high runoffs.

4. Limestone barrier performance was more efficient at installations where the barriers were long, continuous structures and stream flow patterns were diverted by horizontal or vertical baffles than it was for the short, multiple unit installations set in series in the main channel.

5. Limestone barriers are most efficient when they are intially installed, or after they have been reconditioned.

6. There is a reduction in limestone reactivity that results in deterioration of barrier performance after the structures have been in service for some time following initial construction, and again after they have been reconditioned.

7. The rate of deterioration of limestone barrier performance is apparently due to two major factors:

    (a) Siltation whereby sediment accumulations of either silt or iron sludges clog interstices of stones, and

    (b) Coating of the surfaces of the stones with silt or iron hydroxides.

In view of the deficiencies in performance of the limestone barriers on the Trough Creek Project, it is questionable whether it is feasible to attempt to provide in-stream limestone barriers exclusively as the treatment method for area-wide mine drainage pollution abatement, even though the chemical characteristics of the acid waters appear suitable to treatment with limestone. Rather, it is believed that construction of limestone barriers in conjunction with other watershed improvements, such as backfilling strip mined areas, replanting and possibly some mine sealing, would be a more practical approach to regional mine drainage pollution abatement, where the watershed areas and runoff characteristics are similar to those of Trough Creek.

SECTION II

RECOMMENDATIONS

The process of in-stream neutralization of acid mine drainage by limestone barriers should be limited to waters having very low iron concentrations. For the Trough Creek Project, limestone reactivity was apparently unaffected by armoring of the surfaces of the stones with iron hydroxides where the iron concentration of the raw water was approximately 1 mg/l. At one of the barrier installation sites the iron concentration was approximately 30 mg/l, and accumulations of iron sludges in the limestone bed caused almost complete deterioration of barrier performance within a period of three months. Additional research could possibly establish the maximum permissible iron concentration for satisfactory limestone barrier treatment of acid mine drainage.

In the design of limestone barriers, acknowledgment must be made of the fact that where watershed conditions are such that muddy and silt-laden streamflows will be experienced, sediment accumulations will progressively seal the limestone beds, and the surfaces of the stones will become coated with silt. These conditions will result in a reduction in limestone reactivity and barrier performance will deteriorate below theoretical efficiency. The following recommendations are offered in this regard:

1. The designer should size the units sufficiently large to overcome this deficiency.

2. A maintenance program should be established to periodically recondition the barriers to restore them to approximate original condition so that barrier performance will not deteriorate below required efficiency.

SECTION III

INTRODUCTION

GENERAL

Acid mine drainage has long been a pollutant in coal mining areas with the resultant elimination of most aquatic life in streams, together with the attendant problems of prevention of natural bio-oxidation of organic wastes, increased pollutional loadings in receiving waterways, and high treatment costs when water is withdrawn for human use. In the United States the public has recognized the ruinous capacity of coal mine drainage, and laws have been enacted to force the coal industry to treat mine drainage before discharge to natural watercourses. However, there are thousands of abandoned mines in the coal fields that continue to generate acid mine water that discharges directly, without any degree of treatment, to small streams and tributaries. In many of these waters the acidity is less than 100 mg/l, and the iron content is low.

In the late 1960's the Pennsylvania Department of Mines and Mineral Industries (now the Pennsylvania Department of Environmental Resources) became very much interested in research conducted at The Pennsylvania State University in the field of neutralization of acids by percolation of synthetic iron-free acid waters through beds of crushed limestone. (1) Laboratory results of these studies indicated that 100 mg/l of acidity could be significantly reduced by percolation of the water through limestone barriers of short length.

Trough Creek, which is located in South Central Pennsylvania, was selected for a prototype limestone barrier installation project, because the acid waters in the upper reaches of this stream exhibited chemical characteristics similar to the synthetic waters used in the laboratory studies and appeared to be suitable for treatment with crushed limestone. (For location - see Figure 1.)

A mine drainage pollution abatement program for Trough Creek had been estimated by the Commonwealth of Pennsylvania to cost in excess of 1.2 million dollars, with average annual maintenance costs of approximately one-hundred thousand dollars. This program would have included deep mine sealing, backfilling, channel improvement and treatment by lime neutralization of the remaining pollution load. Because of the low iron and sulfate concentrations of the waters of Trough Creek, it was believed that the possibility of reduction of the mineral acidity of the stream with limestone should be pursued, and the Pennsylvania Department of Mines and Mineral Industries engaged the Firm of Africa Engineering Associates, Inc., of Huntingdon, Pennsylvania, to provide consulting

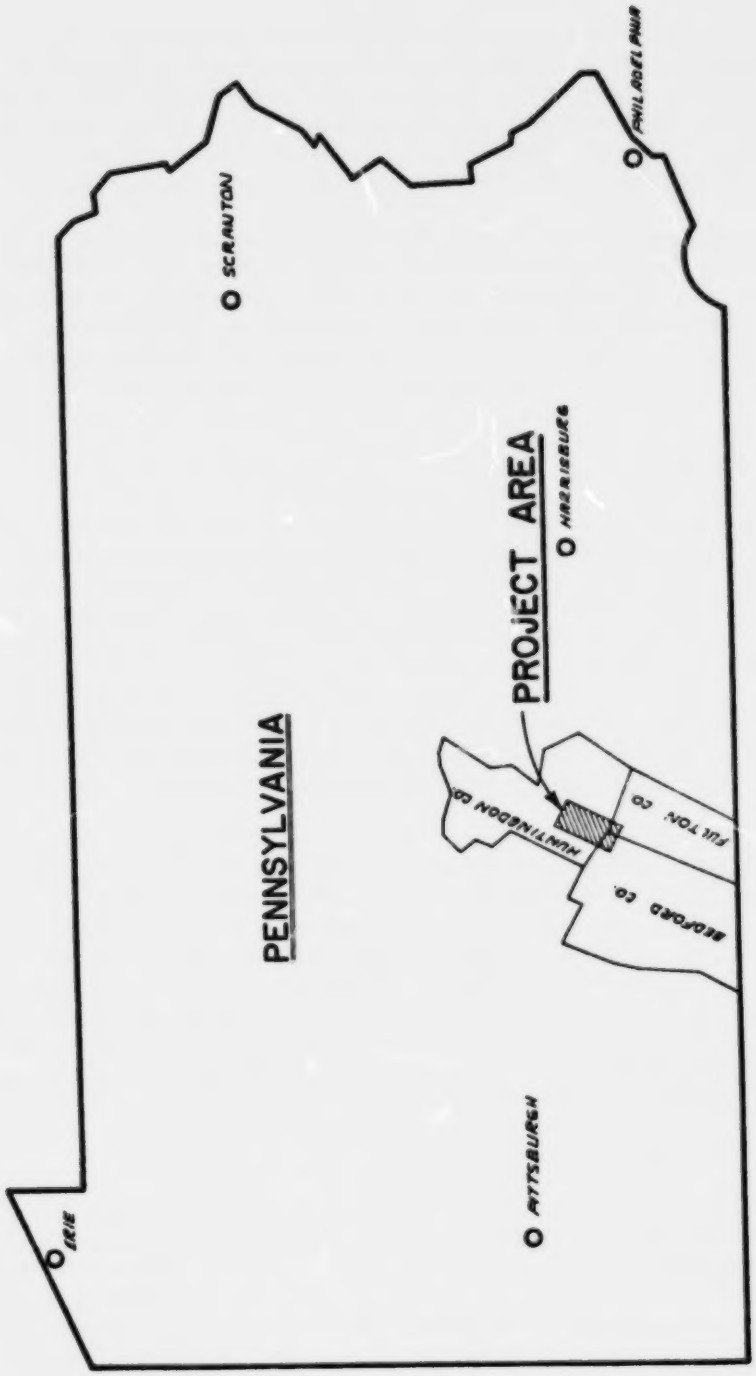

FIGURE 1 - PROJECT LOCATION

engineering services in connection with the investigation and proposed project. Based on the aforementioned research work performed at The Pennsylvania State University, together with watershed investigations conducted by the Commonwealth of Pennsylvania, and field observations, the consultants found it feasible to construct limestone barrier installations at six locations in the headwaters of the basin.

The preliminary engineering estimate of the cost of construction of the Trough Creek Limestone Barrier Installation Project was $172,000. It was felt that if the limestone barriers were successful in reducing stream pollution from acid mine water drainage in Trough Creek, the process could be the key to low-cost treatment of similar polluted streams in other parts of the Commonwealth of Pennsylvania and the Nation.

PURPOSE AND SCOPE

The purpose of this investigation and study is to evaluate the effectiveness and performance of the Trough Creek prototype limestone barrier installations. The evaluations of the barriers developed herein are based on the results of stream gaging and sampling, analyses of selected limestone samples placed in the barriers, and field observations of the completed structures under actual stream conditions during the study period. The purpose also is to assess the adequacy or inadequacy of the design based on the degree to which the barriers demonstrated their ability of reducing the mineral acidity in the stream in relation to performances expected from laboratory research studies.

This report includes a background summary and discussion of the engineering design of the limestone barriers, including site selections, and comments regarding construction. During the course of the construction phase of the Project the barriers experienced severe flooding conditions in June 1972 as a result of Tropical Storm Agnes, and additional work was authorized by the Commonwealth of Pennsylvania to repair and recondition some of the barriers. Included as supplementary information to this report is a tabulation of construction costs of the original project, together with unit costs of reconditioning and repairing limestone barrier damages occasioned by the June 1972 flood.

LOCATION AND GENERAL BACKGROUND INFORMATION

The headwaters of Trough Creek begin in Bedford, Fulton and Huntingdon Counties in South Central Pennsylvania. The area has had extensive deep and surface bituminous mining operations in the Broad Top Coal Field. The surface mining contributed greatly to the pollution loads from abandoned deep mines by diversion and interception of surface water. The water quality problem in the stream is that of acid. Generally, the iron concentrations are less than 1 mg/l, with corresponding

low concentrations of sulfate. Manganese and aluminum are not present except for minute quantities. The stream is devoid of fish life in the upper reaches due to mine drainage. Trough Creek is a tributary to the Raystown Branch of the Juniata River, which is a sub-basin of the Susquehanna River. Trough Creek initially follows a northeasterly and northwesterly circuitous route. At its mouth, the stream bed is Elevation 670, U.S.G.S. Datum. The total length of Trough Creek is approximately 48 kilometers (30 miles), and the watershed is mountainous with narrow valleys flanked with steep hills with some widening of the basin in the vicinity of Little Trough Creek. The stream flows through shale and sandstone formations which contain the previously mentioned bituminous Broad Top Coal Field. The average stream profile is 5.2 meters per kilometer (27.2 feet per mile). The annual precipitation ranges between 89 and 114 centemeters (35 and 45 inches).

The Project received its initial impetus from the conservation subcommittee of the Huntingdon County Planning Commission. Finances for construction of the Project were provided from the $500 million bond issue previously passed by the Pennsylvania Legislature to support "Operation Scarlift" in the Commonwealth.

CONSTRUCTION PHASE AND SAMPLING PROGRAM

The limestone barriers were constructed at six sites in the upper area of the Trough Creek Watershed (see Location Map - Figure 2). Construction of the limestone barriers was started at Site No. 1, the uppermost site in the watershed, on July 27, 1970 and progressed downstream. All work under the original contract was completed on November 26, 1971. Extra work, including placement of additional stone rip-rap along creek banks, limestone media replacement, and heavy rock fills, was authorized after completion of the original contract, and this work was completed in May 1972. In June 1972 severe flooding occurred throughout the watershed as a result of Tropical Storm Agnes, causing scouring of the crushed limestone materials, siltation, some erosion at creek banks, and movement of some of the rock fills on the downstream faces of the barriers which were used to contain the crushed limestone. At Site Nos. 1, 2 and 4 flood damages were repaired and the barriers restored to approximate original condition. This work was started in September 1972 and completed in December 1972 as an extension of the original contract.

The stream gaging and sampling to evaluate the effectiveness of the barriers began in October 1970 before any limestone had been placed, and continued through August 1974. During that period, the limestone barriers were constructed and water samples were collected for analysis on a monthly basis. The stream sampling program consisted of collecting water samples upstream and downstream from the barriers at the various installations and recording rate of stream flow. Selected samples of limestone were placed in the barriers and periodically removed, weighed

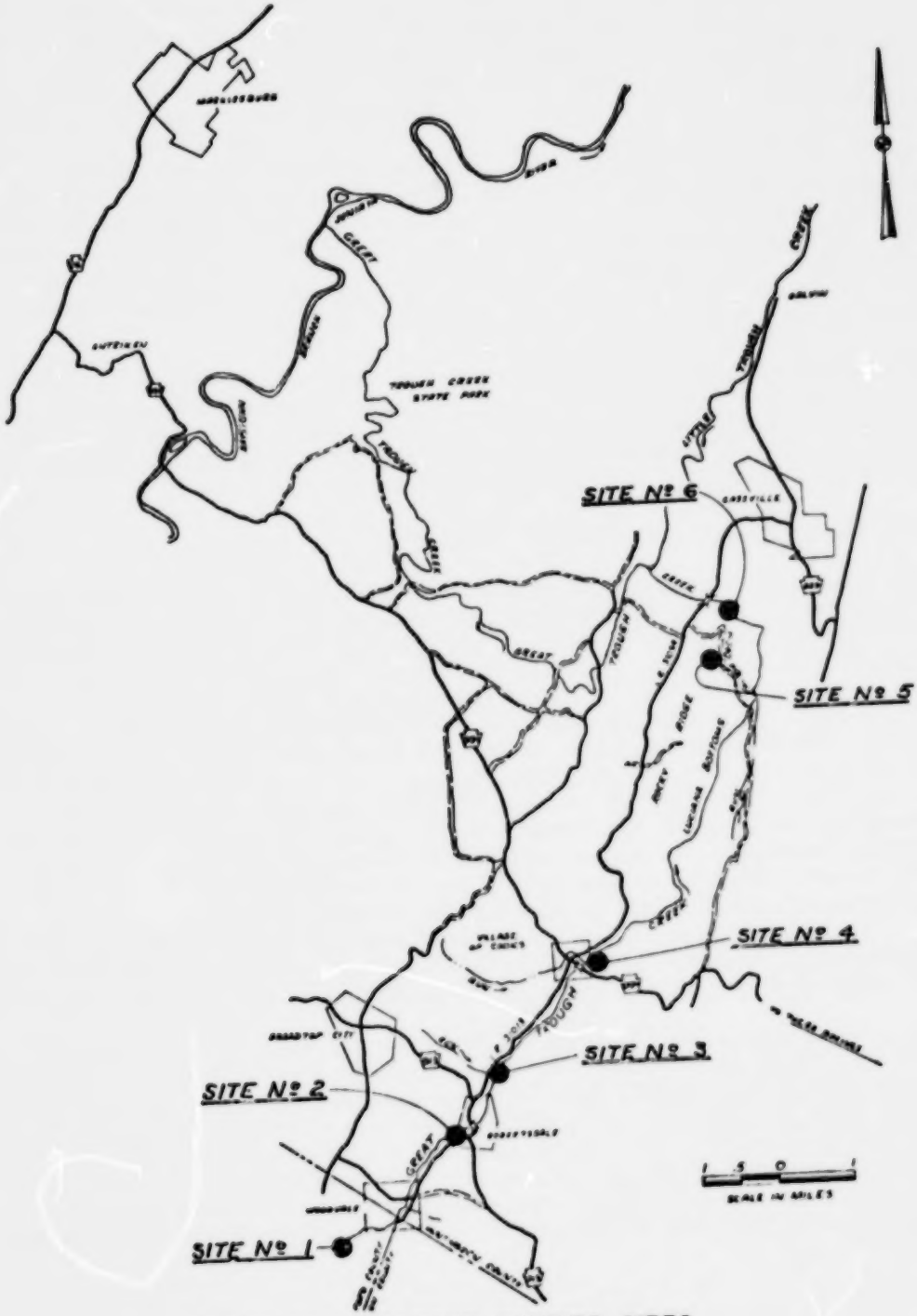

FIGURE 2 - LIMESTONE BARRIER SITES

and replaced to attempt to determine loss of weight of limestone, as a function of time.

SECTION IV

LIMESTONE BARRIER DESIGN

GENERAL

The basis of design of the Trough Creek Limestone Barriers was the aforementioned research data that was developed in the late 1960's at The Pennsylvania State University, which formulated inter-relationships between acid concentrations, rate of neutralization, stone size, and stream velocity.

In the design of the limestone barriers, consideration was given to the possibility of siltation of the crushed limestone materials and scouring during periods of high stream flow. It was recognized that either of these conditions could render the installations ineffectual in terms of their ability to reduce the mineral acidity of the stream; however, it was also noted at that time that the proposed project to be undertaken was somewhat experimental in nature, and that the data to be derived therefrom could provide valuable information in the design of future installations of similar types, if the process proved practicable.

Generally, the limestone barrier structures are miniature porous dams, set within the stream channel, and consist of cores of crushed limestone contained by heavy rock fills on the upstream and downstream faces.

WATERSHED INVESTIGATION AND SELECTION OF LIMESTONE BARRIER SITES

Prior to retaining the consultant for engineering design and preparation of drawings and contract documents for construction of the Trough Creek Limestone Barriers, the Department of Mines and Mineral Industries of the Commonwealth of Pennsylvania conducted an investigation of mine drainage throughout the watershed in April and May 1968. This investigation included stream gaging and water sampling of the stream, tributaries, and at sources of mine seepage.

The watershed investigation conducted by the Commonwealth of Pennsylvania indicated that Trough Creek was considered to be alkaline from Trough Creek State Park to its confluence with the Raystown Branch of the Juniata River near Marklesburg, Pennsylvania, and that it was considered to be acid for approximately 22.5 kilometers (14 miles) in the upper reaches. The farthermost downstream point of discharge of acid mine drainage to Trough Creek was found to be the overflow of an abandoned drift mine, hereinafter described as Limestone Barrier - Site No. 5.

Except for the overflow discharge from the abandoned mine at Site No. 5, results of chemical analyses of water samples collected throughout the acid mine discharge areas during the watershed investigation showed that the pH range of the waters of Trough Creek and the Run leading from Broad Top City varied between approximately 3.2 and 5.4; acidity varied between approximately 5 and 22 mg/l; sulfates varied between approximately 20 and 40 mg/l; and (total) iron concentrations were generally less than one mg/l. The concentrations of pollution loads from the overflow discharge at the abandoned mine at Site No. 5 were found to be approximately 270 mg/l of acidity and 30 mg/l total iron. However, the rate of flow of the abandoned mine discharge was quite low in comparison to the flow in Trough Creek.

On the basis of the watershed investigation, field inspections, and consultations with the research personnel at The Pennsylvania State University, six (6) sites were selected in the upper area of the Trough Creek watershed for limestone barrier installations. These Sites are briefly described in Table 1, and are shown on Figure 2.

Table 1. SITE LOCATIONS - TROUGH CREEK LIMESTONE BARRIERS

SITE NO.	LOCATION AND DESCRIPTION
1	Trough Creek - Approximately 183 meters (600') upstream from Village of Woodvale at the spillway of an abandoned reservoir.
2	Trough Creek - Robertsdale - 274 meters (900') more or less, upstream from bridge at Post Office.
3	Trough Creek - 0.8 kilometers (0.5 mile) more or less, north of Robertsdale at junction of Trough Creek and tributary from Broad Top City.
4	Trough Creek - 3 kilometers (2 miles) more or less, north of Robertsdale at Village of Cooks at junction of Trough Creek and small tributary. Barrier to be located immediately downstream from bridge on Route 994.
5	Tributary draining to Luciana Bottoms, approximately 3 kilometers (2 miles) south of Cassville. Barrier to be located at drainage outlet of old Jacobs Mine.
6	Trough Creek - Upstream from bridge where Trough Creek crosses L.R. 31094.

In selecting the limestone barrier sites, priority was given to accessibility and close proximity to existing roadways for economical

construction and maintenance. Also of primary concern in the selection of barrier locations was topography in the areas adjacent to the proposed sites. Consideration was given to the possibilty of ponding of a few feet additional depth of water upstream from the barriers, and it was believed that minimum property damage would result from the stream obstructions at the sites selected.

ENGINEERING DESIGN - LIMESTONE BARRIERS

General guidelines for the design of the Trough Creek Limestone Barriers were established as an outgrowth of preliminary conferences with University research personnel, Commonwealth of Pennsylvania Officials, and the consultant, as follows:

1. Design flows through the barriers should be determined on the basis of approximately one-hundred twenty-five (125%) percent of the computed average stream flow.

2. Design acid loadings, in terms of pounds per day, at the various limestone barrier sites should be determined on the basis of approximately one-hundred twenty-five (125%) percent times computed loadings at average stream flow.

3. Crushed limestone should be furnished in sufficient quantities to provide for a theoretical 5-year limestone consumption or replacement program, based on the specified calcium carbonate content of limestone.

4. Although the use of graded limestone of the smaller sizes (2.5 cm or 1 inch in size) was recommended in the research studies because of the greater surface (contact) area and resultant higher neutralization rates, it was decided to use larger stone sizes (6.35 to 10.16 cm or 2 1/2 to 4 inches) in the barriers to be erected in the stream because the larger stones would provide greater stability and be less susceptible to washing and scouring during periods of high stream flow. At Site No. 5, where the flow was known to be low and relatively constant, it was decided to use the smaller stone size.

5. The limestone barriers at Site No. 6, and to some extent the barriers at Site No. 4, should be erected to provide additional insurance if upstream installations failed or would not provide expected degree of treatment.

6. Limitations of the Pennsylvania Department of Forests and Waters (now Department of Environmental Resources) regarding encroachments and stream obstructions in the waters of the Commonwealth must be strictly adhered to.

7. Inasmuch as a follow-up water sampling and stream gaging program to evaluate the effectiveness of the limestone barrier installations was contemplated during the planning phase of the project, it was decided that measuring flumes of constant cross-section should be installed in the stream for the purpose of measuring stream flow by the velocity-area method.

Detailed design of the Trough Creek Limestone Barriers was based on inter-relationships of stone size, rate of flow, barrier length, superficial velocity, retention time, and initial acidity. The six working equations that were developed as a result of the research in the late 1960's at the Pennsylvania State University are as follows:

$$U = 0.353D_p + 0.566Q_p - 0.0292L_p + 1.060$$

$$T = 0.265D_p^{-0.366}\ Q_p^{-0.477}\ L_p^{\ 1.35}$$

$$K = 0.55C^{-0.17}{}_U{}^{-0.74}{}_D{}^{-0.84}$$

$$C_f = C_i\ (1-K)^T$$

$$H_p = -0.580D_p + 0.584Q_p + 0.0376L_p + 1.521$$

$$S = 0.417D_p^{-0.931}\ Q_p^{\ 0.921}\ L_p^{\ -0.562}$$

where, U = average superficial velocity, fps

D_p = stone size, inches

Q_p = flow rate, cfs/ft

L_p = barrier length, feet

T = retention time, seconds

K = fractional acid reduction, sec^{-1}

C_i = initial acidity, mg/l

C_f = final acidity, mg/l

H_p = head water depth, feet

S = water surface slope

Hydraulic profiles, computed from the above relationships, were

investigated under varying rates of flow through the barriers. Where necessary, the slopes of stream beds were altered to provide ample head between the upstream and downstream limits so that the hydraulic gradient at design (average x 1.25) flow was uninterrupted through the barriers.

Determination of Design Flows

The Pennsylvania Department of Forests and Waters (now the Pennsylvania Department of Environmental Resources) maintained a stream gaging station for the period 1930 to 1957 on Great Trough Creek at a highway bridge, 0.8 kilometers (0.5 miles) upstream from the confluence of Great Trough Creek and the Raystown Branch of the Juniata River. Information contained in the 1966 edition of the Pennsylvania Department of Forests and Waters "Bulletin No. 1, Water Resources Bulletin, Pennsylvania Streamflow Characteristics - Low Flow and Flow Duration" for the Great Trough Creek Gaging Station was the basis for determining design stream flows at the various limestone barrier sites.

Following is a tabulation of pertinent data relative to stream flow characteristics at the Great Trough Creek Gaging Station:

Drainage Area	219.1 km^2 (84.6 sq. mi.)
Average Discharge (27 years)	2.7 m^3/s (95.1 cfs)
Max. Discharge (Mar. 17, 1936)	238 m^3/s (8,400 cfs)
Min. Discharge (3 occasions)	0.02 m^3/s (0.6 cfs)

By interpolation from the Duration Table of Daily Flow in the Bulletin, the average (27 year) discharge was exceeded 29.4 percent of the time.

Design (average x 1.25) flows for the limestone barriers were computed by assuming uniform runoff conditions throughout the watershed, determining the contributary drainage area above each site by planimeter on U.S.G.S. Maps, and by applying an average discharge rate of 1.232×10^{-2} m^3/s per square kilometer (2.7 $m^3/s \div 219.1$ km^2) or 1.124 cfs/sq. mile (95.1 cfs ÷ 84.6 sq. mi.). Design Flows are tabulated in Table 2.

Table 2. DESIGN FLOWS - TROUGH CREEK LIMESTONE BARRIERS

Site No.	(1) Drainage Area (Sq. Mi.)	(2) Average Flow (cfs)	(3) Design Flow (cfs)	Cumulative Design Flow (cfs)
1	6.05	6.8	8.5	8.5
2	4.10	4.6	5.8	14.3
3	3.45*	3.9*	4.9*	19.2*
4	3.66	4.1	5.1	24.3
6	7.06**	7.9**	9.9**	34.2**

NOTE: To convert square miles to square kilometers, multiply square miles x 2.59. To convert cfs to m^3/s, multiply cfs x 0.02832.

(1) Incremental contributory drainage area upstream from each site
(2) Computed - 1.124 cfs/sq. mi.
(3) 1.25 x computed average flow

*Includes Run from Broad Top City on which Limestone Barrier No. 3-C was erected. The design flow for this Barrier was 3.0 cfs, and is included in the cumulative (19.2 cfs) flow for Barriers Nos. 3A and 3B.

**Includes watershed area of 0.22 sq. mi. above Site No. 5, which drains to Trough Creek between Sites Nos. 4 and 6. Design Flow of 0.4 cfs used for overflow at abandoned mine at Site No. 5.

Design Acid Loadings - Limestone Barriers

Acid loadings used for design at the various limestone barrier sites were determined from results of analyses of the preliminary water sampling and stream gaging investigations of the watershed.

The stream flows that were recorded at the time of the watershed investigation were slightly different than the computed design average flows; however, the acid concentrations of water samples collected at the proposed limestone barrier sites were used to determine the design acid loadings. As previously mentioned, the design acid loadings were determined by increasing computed acid loadings by approximately 25 percent at all sites, except that the barriers to be erected at Site Nos. 4 and 6 were to be furnished primarily to provide additional insurance if

upstream installations failed to yield expected degree of treatment.

Table 3 shows the design acid loadings at the various limestone barrier sites.

Table 3. DESIGN ACID LOADINGS - TROUGH CREEK LIMESTONE BARRIERS

Site No.	(1) Computed Acid Loading (lbs/day)	(2) Design Acid Loading (lbs/day)	(3) 5-Year Acid Design Loading (lbs. x 10^3)
1	733	900	1,650
2	42	50	100
3A & 3B*	130	165	300
3C**	68	85	150
4	50	50	100
5	584	730	1,330
6	-	-	-
Totals	1,607	1,980	3,630 (1,865 Tons) (1,693 Metric Tons)

NOTE: To convert pounds (lbs) to kilograms, multiply pounds x 0.4536.

*Limestone Barriers in Trough Creek
**Run from Broad Top City

(1) Incremental acid loading between each site
(2) 1.25 x computed load
(3) 5-year acid loading shown to nearest 50 x 10^3 pounds

Crushed Limestone

Since the Trough Creek Limestone Barrier Installation Project was a prototype project undertaken as a result of research, it was deemed necessary that the limestone materials to be furnished for the barriers should not only be effective as a neutralizing agent, but also it was believed desirable that the materials should be similar in chemical composition to those used in the research studies. The crushed limestone that was used for the University research work at State College, Pennsylvania, was Valentine Limestone, and was obtained from the Appalachian Stone Quarry (Division of Martin Marietta). This quarry is located at Pleasant Gap, Pennsylvania, approximately 14.5 kilometers (9 miles)

northeast of the University; however, the quarry is located approximately 105 kilometers (65 miles) from the Trough Creek Project area. A typical analysis of Valentine Limestone was furnished by the supplier and is shown in Table 4.

Table 4. VALENTINE LIMESTONE ANALYSIS

Substance	Percent by Weight
$CaCO_3$	96.800
$MgCO_3$	1.630
SiO_2	0.800
R_2O_3	0.500
P	0.003
S	0.035

During preparation of the Contract Specifications for construction of the Trough Creek Limestone Barrier Installation Project an effort was made to locate a suitable source of limestone (high in calcium carbonate) close to the Project area to minimize haulage and keep construction costs as low as possible. However, it was found that limestones in active quarries in Central Pennsylvania near the Project area were dolomitic limestones, high in magnesium carbonate (approximately 30 to 40 percent by weight), and according to previous research studies, would probably not be as effective a neutralizing agent as the limestones from the Appalachian Stone Quarry. With the foreknowledge that construction costs would be somewhat higher than originally expected because of long hauls for delivery of materials, the Contract Specifications stipulated that the calcium carbonate content of the limestone to be furnished for the barriers shall not be less than 95 percent by weight.

As previously noted under the general guidelines for design of the barriers, it was decided that crushed limestone should be furnished in sufficient quantities to provide for a theoretical 5-year replacement based on the calcium carbonate content of the limestone; and that the barriers at Site No. 6, and to some extent the barriers at Site No. 4, should be erected to provide additional insurance if upstream installations failed or would not provide the expected degree of treatment. Also, the size and shape of the barriers was governed by site topography and limitations of the Commonwealth of Pennsylvania regarding stream obstructions. Table 5 shows a tabulation of the theoretical 5-year quantity of limestone required at each site compared to the amount actually provided. The amounts provided, as shown in the Table, are quantities computed from the detailed contract drawings.

Table 5. QUANTITY OF LIMESTONE PROVIDED TROUGH CREEK LIMESTONE BARRIERS

Site No.	(1) 5-year Acid Loading (lbs. x 10^3)	(2) Limestone Required 5-year Replacement (c.f.)	(3) Quantity of Limestone Provided (c.f.)
1	1,650	19,470	13,300
2	100	1,180	4,600
3	450	5,310	6,100
4	100	1,180	15,300
5	1,330	15,700	16,800
6	-	-	29,000

NOTE: To convert pounds (lbs.) to kilograms, multiply pounds x 0.4536
To convert cubic feet (c.f.) to m^3, multiply c.f. x 0.02832

(1) Reference Table 3
(2) Computed quantity based on the following limestone properties:

96% $CaCO_3$
Specific Gravity = 2.7
53% Solids

(3) Determined from detailed Contract Drawings

Although the quantity of limestone furnished at Site No. 1 was less than the theoretical 5-year computed quantity, it was believed to be adequate because it did provide limestone for a calculated 3.4 year supply, and surplus materials were being furnished at other downstream sites.

Gaging Flumes - Measurement of Stream Flow

Gaging flumes of constant cross-section were proposed at each site so that during the sampling program the rate of flow could be measured by the velocity-area method in the main channel and tributaries. The gaging flumes were proposed to be grouted stone rip-rap construction, 7.6 meters (25 feet) in length, and the slope of the invert to be 0.40 percent. The cross-sections of the flumes at the various sites were sized on the basis of the following design criteria.

1. Design (flood) flows to be computed from upstream contributary drainage areas and proportioned to the maximum discharge rate of 238 m^3/s (8400 cfs) for the watershed having a drainage area of 219.1 square

kilometers (84.6 sq. mi.) and which was recorded March 17, 1936 at the Great Trough Creek Gaging Station.

2. Depth of water in the proposed flume channels to be approximately 0.3 meters (one foot) at computed average stream flow.

3. Use n = 0.015 in the Kutter formula for grouted stone masonry, and n = 0.013 for vitrified clay channel pipes.

All flumes were sized to accomodate design flood flows. Wherever possible, the flumes were installed upstream from the barriers such that the profile of the hydraulic gradient of stream flow through the flumes would be unaffected by any water build-up on the upstream faces of the barriers at design (average x 1.25) flow. Where topography dictated that flumes be installed downstream from the barriers, they were positioned low enough so that the profile of the hydraulic gradient of stream flow through the barriers would be unaffected by flow through the flumes at computed average streamflow.

Comments Regarding Design

The undertaking of construction of the prototype Trough Creek Limestone Barriers for the purpose of neutralizing acid mine drainage by the process of in-stream treatment with crushed limestone was the first such endeavor for an entire watershed pollution abatement project where the range of stream flow was of the magnitude of Trough Creek. At the outset, it was recognized that there were a number of uncertainties associated with the project that suggested potential problem areas, such as possible siltation, erosion, and scouring of the crushed limestone. Furthermore, it was not known if a certain degree of armoring of the surfaces of the limestone might occur where the materials remained undisturbed for long periods of time, even though the iron concentrations were low.

In attempting to establish the general guidelines for engineering design of the Trough Creek Limestone Barriers, acknowledgment was made of the fact that normally stream sampling in connection with design is more comprehensive in scope than that performed for this project at the proposed barrier sites. A more extensive preliminary water sampling program at the proposed barrier sites may have altered somewhat the design acid loadings and projected theoretical quantities of limestone required for 5-year replacement. However, in view of the nature of the uncertainties previously noted,together with the lack of factual information pertaining to limestone reactivity and barrier performance under actual stream conditions, it was believed that the additional time that would be involved in conducting a comprehensive water sampling program at each site to determine more precisely the design acid loadings was not

justified. It was also believed that any deficiencies in design criteria developed from laboratory research, together with possible detrimental physical aspects that would render the barriers ineffective, would become manifest in the stream sampling, analysis and evaluation project that would be conducted during and after construction of the limestone barriers.

Barrier Configurations and Details

Topography in the areas adjacent to the proposed limestone barrier sites, together with limitations set forth by the Commonwealth of Pennsylvania regarding channel changes and stream obstructions, dictated to some degree the configurations of the limestone barriers. Also, it was felt that different stream flow patterns and barrier shapes should be incorporated in the design of the Project to see which scheme proved to be the most effective under actual stream conditions in reducing the mineral acidity of the water.

In Pennsylvania it is necessary to obtain a permit from the Department of Environmental Resources to construct any dam or other water obstruction, or in any manner to change or diminish the course, current or cross-section of any stream having a drainage area of more than 1.3 square kilometers (one-half sq. mi.). For the Trough Creek Project a permit was required for each limestone barrier installation, except at Site No. 5 where the drainage area above the site was 0.57 sq. km. (0.22 sq. mi.). General requirements for permit approval for the Trough Creek Limestone Barriers included the following stipulations:

1. Existing stream channels shall be widened and the stream beds reshaped in the limestone fill areas. The extended creek banks shall be lined with heavy rocks to top of bank on each side of the barriers to prevent erosion during periods of high water and scouring stream flow.

2. Limestone barriers shall be constructed to heights not exceeding 0.9 meters (3 ft.) above existing stream bed elevation. In this connection, where it was necessary or desirable to provide limestone fills greater than 0.9 meters in depth, existing stream beds were lowered such that elevation of the top of the barriers was not more than 0.9 meters above existing stream bed.

The proposed limestone barriers at Site No. 1 were located at the outlet end of a shallow abandoned reservoir. The design included horizontal and vertical baffles to provide an extended contact period for the acid water with the crushed limestone.

At Site Nos. 2 and 3 where the creek banks were well defined, two bar-

riers at each site were proposed in series in the main channel of Trough Creek, and one barrier in the Run from Broad Top City at Site No. 3. The barriers at these sites were approximately 7.6 meters (25 ft.) in length and extended from creek bank to creek bank in the stream channel. Rock barriers, consisting of large stones placed in the main channel from creek bank to creek bank, were provided upstream from the limestone barriers for the purpose of collecting floating debris during periods of low and average streamflow.

At Sites Nos. 4 and 6 where the creek banks were not well defined, the design included jetty-type structures to be erected alternately from each creek bank and extending into the main channel. Additional crushed limestone, approximately 0.3 meters (one foot) in depth, was provided in the channel. Horizontal concrete baffle walls and vitrified clay pipe cross drains were proposed to divert low or average streamflows such that a longer contact time for neutralization would be afforded. Stilling basins were provided upstream from the limestone barriers to settle out mud and sediment.

At Site No. 5, the overflow outlet of an abandoned mine, the proposed barrier simply included clearing, excavation, and completely filling the outlet area with crushed limestone to a computed depth such that design flow would be below the surface of the limestone materials.

In March 1970 the Commonwealth of Pennsylvania authorized the advertisement for bids for construction of the Trough Creek Limestone Barrier Installation Project. Details of the limestone barriers at the various sites are shown on Figures 3 to 8 inclusive.[2]

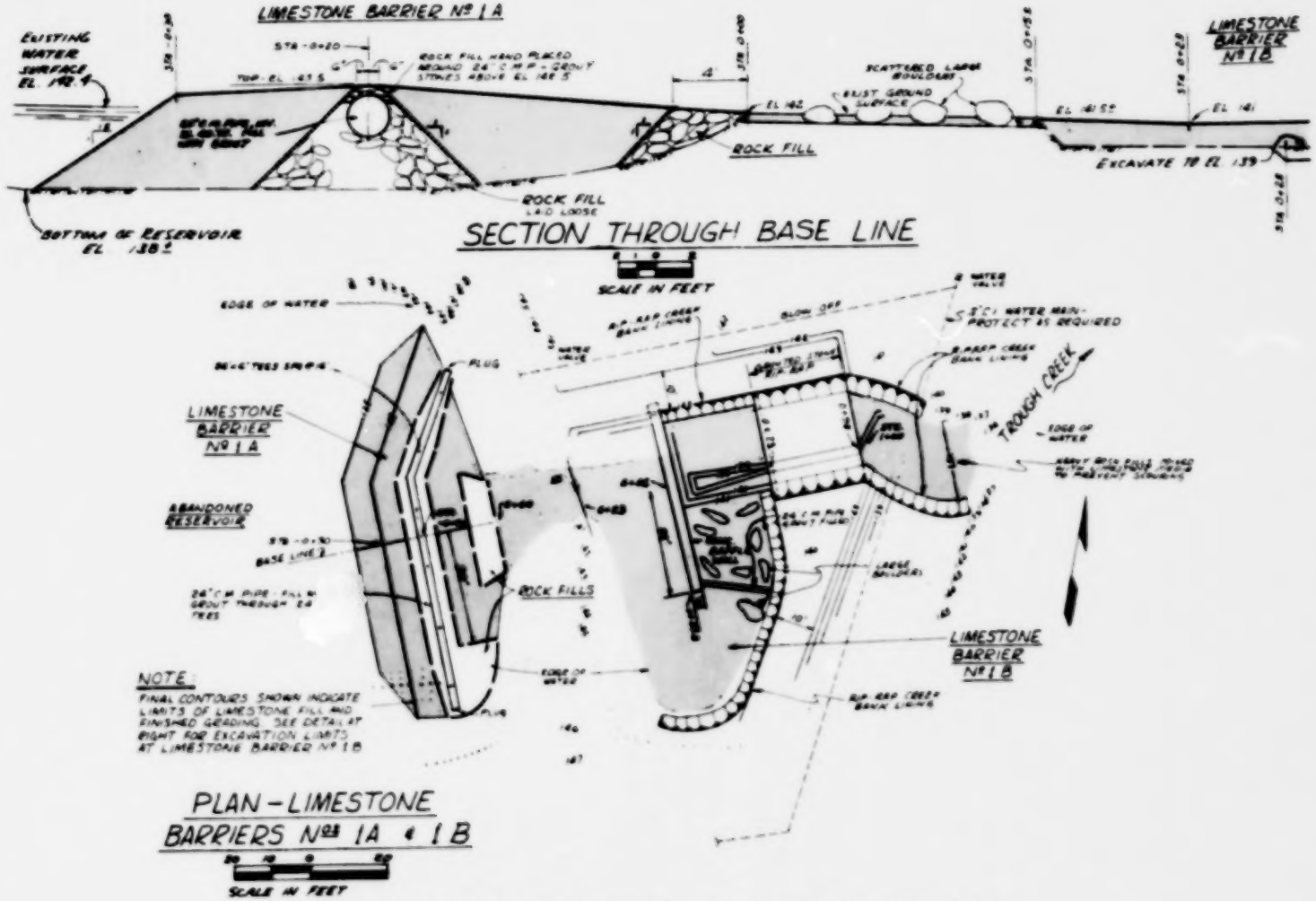
LIMESTONE BARRIER Nº 1 A
EXISTING WATER SURFACE EL. 150.4
ROCK FILL HAND PLACED
ROCK FILL
ROCK FILL LAID LOOSE
BOTTOM OF RESERVOIR EL. 138±
EXCAVATE TO EL. 139
LIMESTONE BARRIER Nº 1B
SECTION THROUGH BASE LINE
SCALE IN FEET
EDGE OF WATER
PLUG
LIMESTONE BARRIER Nº 1 A
ABANDONED RESERVOIR
ROCK FILLS
TROUGH CREEK
LIMESTONE BARRIER Nº 1 B
NOTE
FINAL CONTOURS SHOWN INDICATE LIMITS OF LIMESTONE FILL AND FINISHED GRADING. SEE DETAIL AT RIGHT FOR EXCAVATION LIMITS AT LIMESTONE BARRIER Nº 1 B
PLAN - LIMESTONE BARRIERS Nºs 1A & 1B
SCALE IN FEET

Figure 3. Limestone Barrier Construction Details – Site No. 1

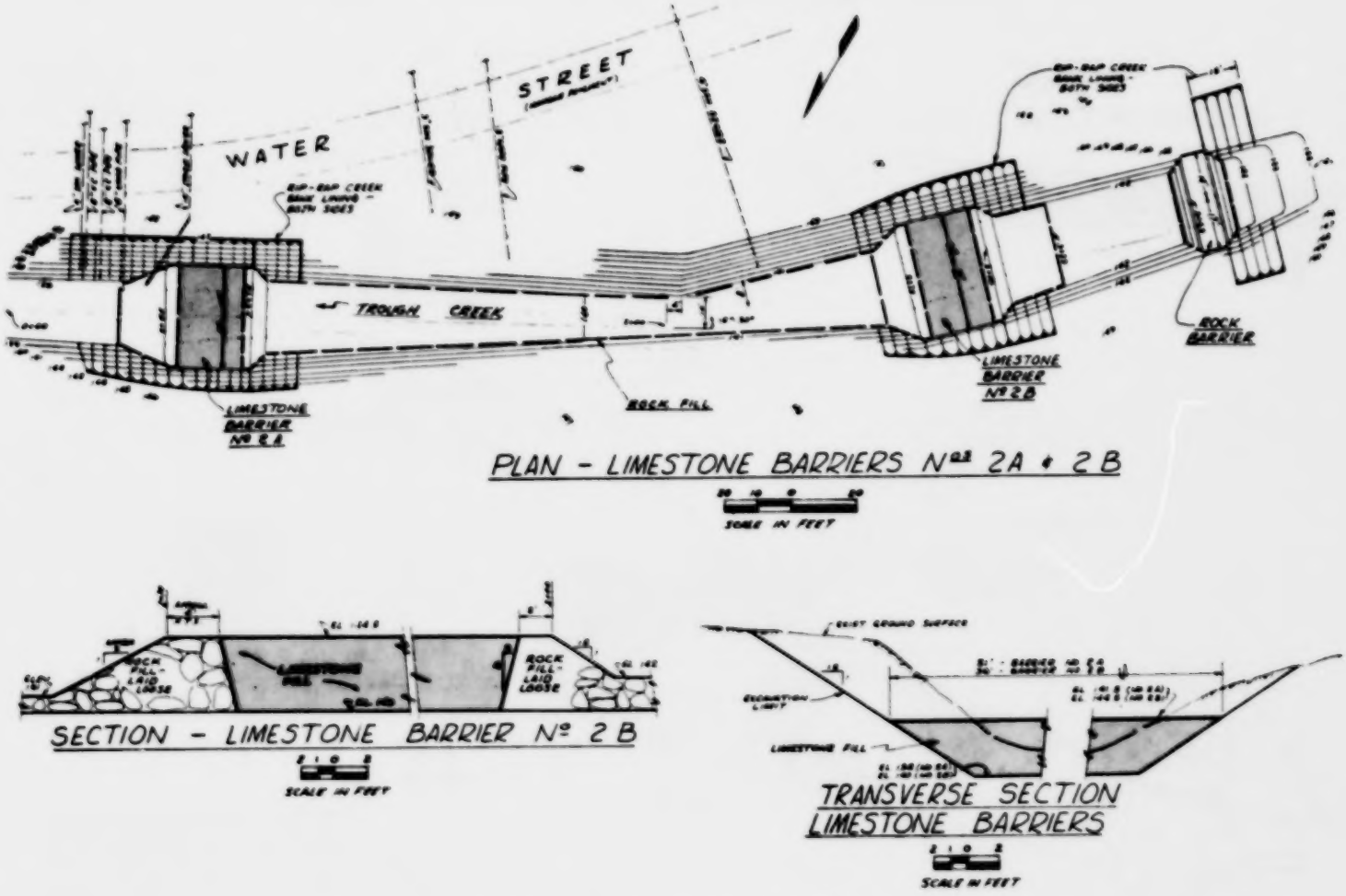

Figure 4. Limestone Barrier Construction Details – Site No. 2

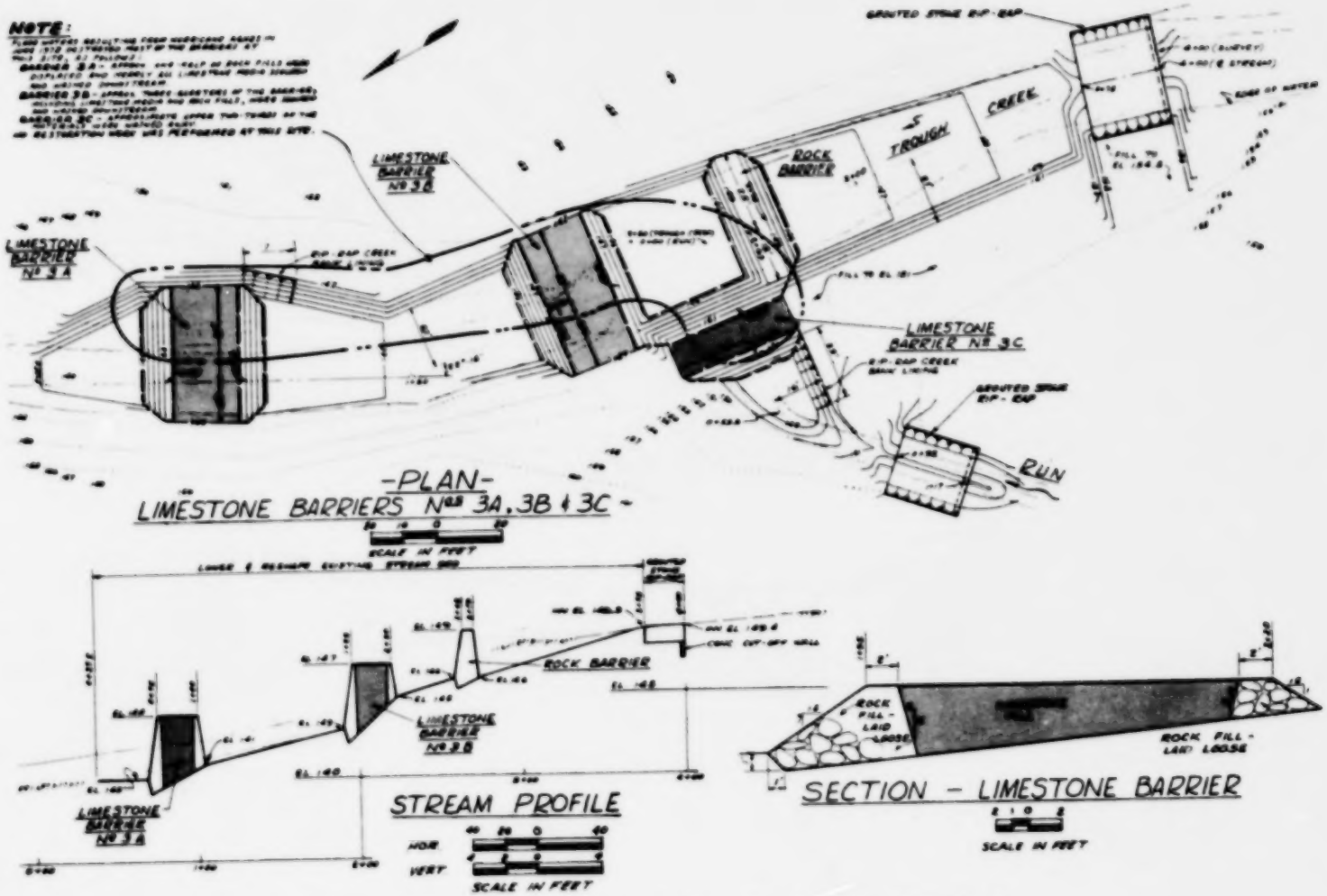

Figure 5. Limestone Barriers Construction Details — Site No. 3

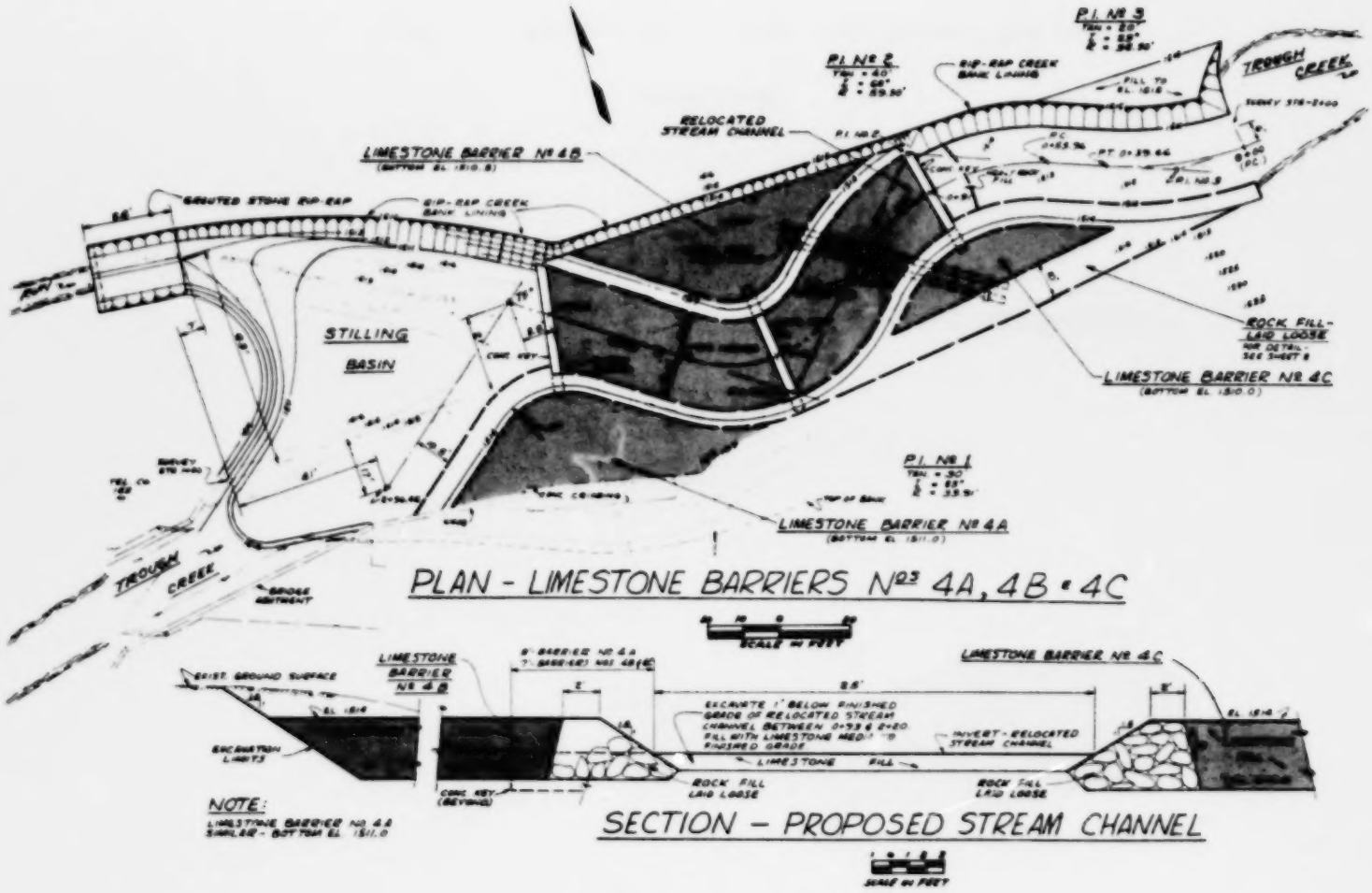

Figure 6. Limestone Barrier Construction Details — Site No. 4

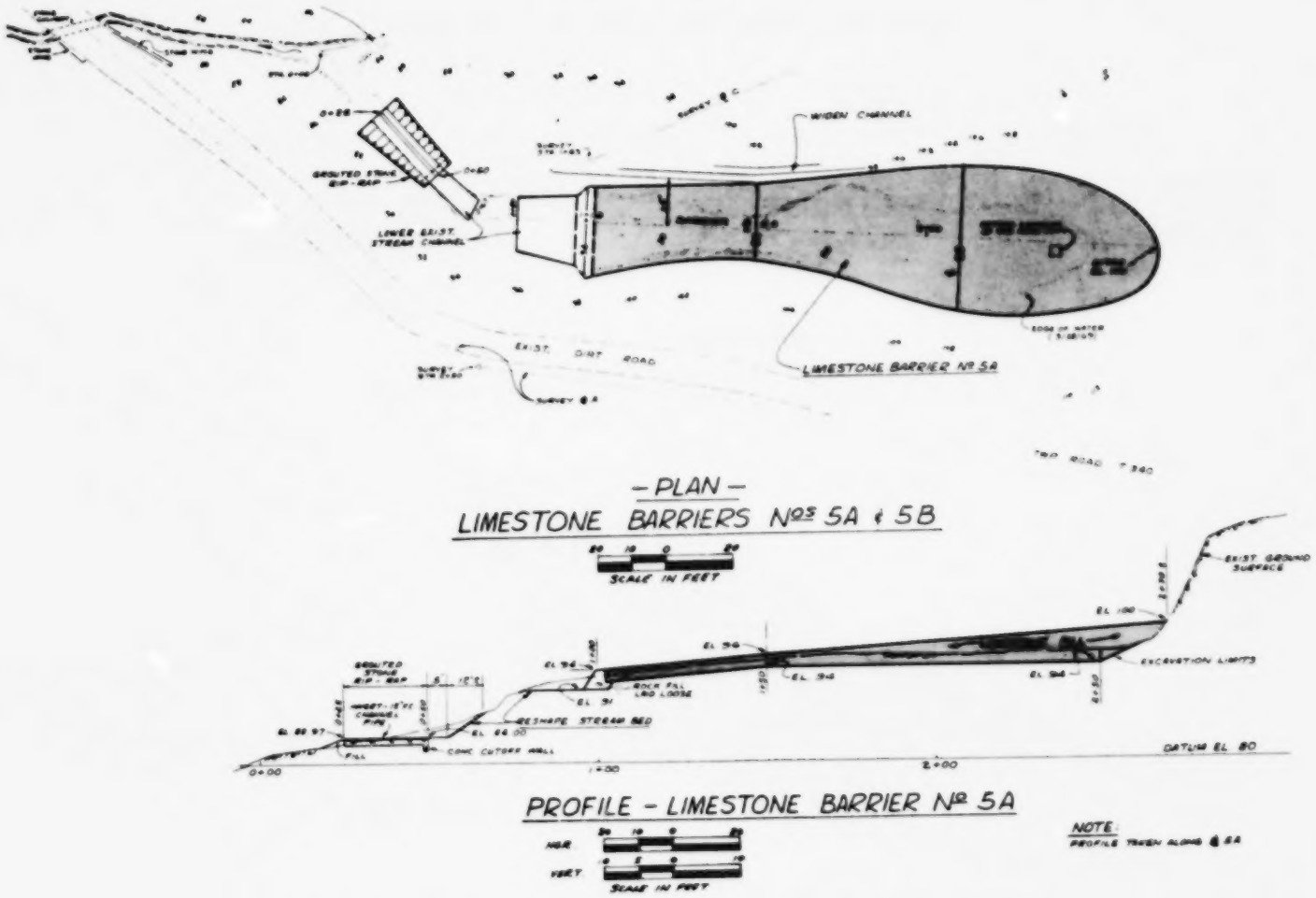

Figure 7. Limestone Barrier Construction Details — Site No. 5

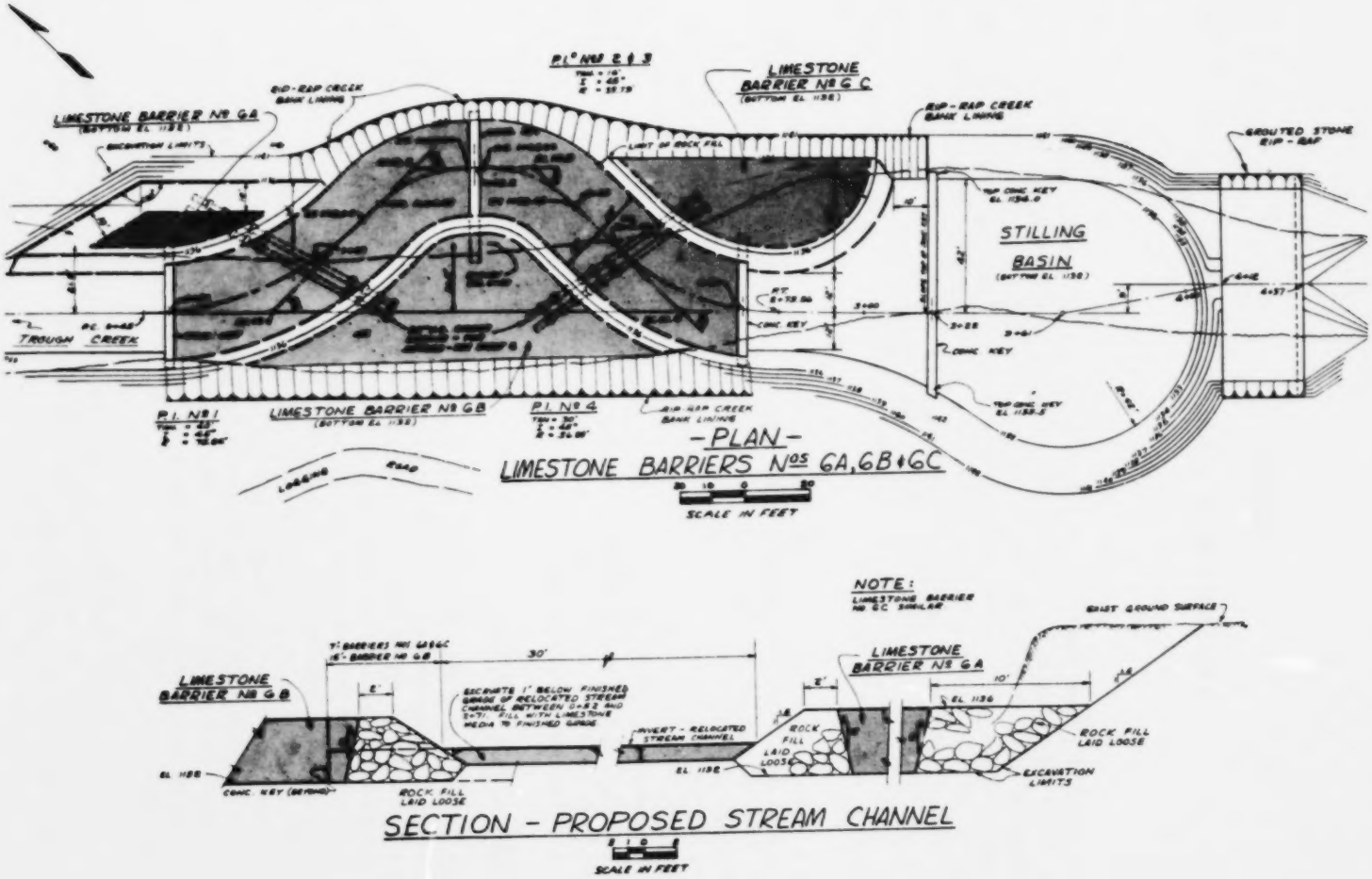

Figure 8. Limestone Barrier Construction Details—Site No. 6

SECTION V

CONSTRUCTION OF LIMESTONE BARRIERS

GENERAL

In June 1970 the Contract for "Construction of Limestone Barriers - Trough Creek Watershed," Contract No. SL-121-1, was awarded by the Commonwealth of Pennsylvania in the amount of $184,450.00. The work under the Contract consisted of construction of limestone barrier installations at six locations in the watershed and included site clearing, stream channel widening and lowering existing stream beds, and the furnishing and placing of stone rip-rap creek bank linings, grouted stone rip-rap gaging flumes, concrete masonry, heavy rock fills, piping, and crushed limestone.

The work was started on July 27, 1970 at Site No. 1, the uppermost site in the watershed, and progressed downstream. The sequence of construction of the barriers at the various sites is shown in SECTION VII, STREAM SAMPLING AND LIMESTONE ANALYSIS, where a correlation is made of the acidity of the waters of Trough Creek relative to installation of the barriers. Construction costs for the original contract plus certain extra work allowances are shown in Table 8 in this Section. A description of limestone barrier damages caused by flooding in 1972 are presented in Section VI, together with measures that were adopted for reconditioning and barrier repairs, and costs of correction.

Construction Requirements

All work on Contract No. SL-121-1 was performed on private property where easement agreements had been previously acquired. The contract included the usual requirements regarding responsibilities in connection with ingress and egress over the properties for the purpose of construction, clean-up, and disposal of waste materials. Limestone barrier installations were constructed, complete, in consecutive order beginning at Site No. 1 and the work proceeded downstream to Site No. 6. At each limestone barrier site all work was completed and stream flow directed through the barriers before the contractor moved his operations to succeeding downstream installations. The contract specifications stipulated that the sequence of such work at each site shall be performed in the following order:

1. Site clearing, including access roadways, and the removal and disposal of trees, stumps, brush and general clearing preparatory to excavation.

2. Excavation, including removal and disposal of all materials

necessary for lowering existing stream beds and relocating stream channels to the lines and subgrades shown on the contract drawings. The Contractor was required to employ such protective measures as were necessary to prevent pollution of the stream with fuels, oils, sediment or other harmful materials. The Contract required that all excavations be completed before placement of rolled fills, stone rip-rap, rock fills, concrete masonry and crushed limestone.

3. Placement of rolled earthen fills.

4. Placement of stone rip-rap on creek banks to prevent bank erosion. The specifications required that at least 30 percent of the stones for rip-rap shall weigh not less than 90.7 kilograms (200 pounds) and at least 20 percent shall weigh more than 9.1 kilograms (20 pounds).

5. Placement of concrete masonry for cut-offs and baffle walls.

6. Placement of rock fills at the proposed upstream and downstream faces of the barriers, and at other locations used to confine and prevent washing of the crushed limestone. The specifications required that at least 60 percent of the stones for rock fills shall weigh not less than 90.7 kilograms (200 pounds) and at least 90 percent of the stones shall weigh more than 9.1 kilograms (20 pounds).

7. Placement of crushed limestone in the barriers was the last step in the sequence of construction at each site. The specifications required that the limestone materials be stored on hard and clean elevated surfaces, sloped to the outer edges to insure proper drainage and to prevent possible accumulations of mud and silt on the stone surfaces during storage. The contract also required that the crushed limestone be placed in the stream as nearly as practicable in its final position. Bulldozing of limestone materials into place, or the traveling over previously placed materials with heavy equipment was prohibited. Placement of the crushed limestone on prepared stream bed surfaces was started at the furthermost point upstream and proceeded downstream. Table 6 shows a chemical analysis of the limestone materials furnished for the Trough Creek Project, and Table 7 shows the sieve analysis of the materials.

Illustrations of the finished limestone barriers, as they appeared shortly after construction was completed, are shown in Figures 9 to 14 inclusive.

FIGURE 9 - COMPLETED LIMESTONE BARRIERS - SITE No. 1

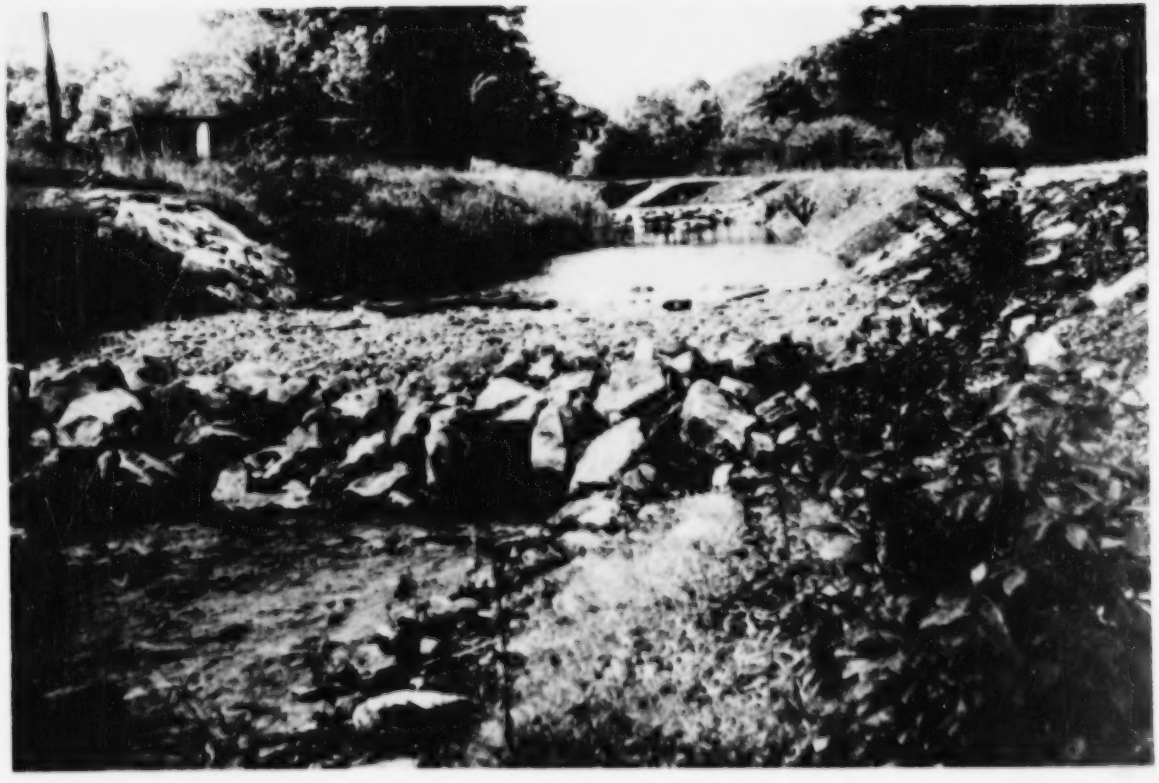

FIGURE 10 - COMPLETED LIMESTONE BARRIERS - SITE No. 2

FIGURE 11 - COMPLETED LIMESTONE BARRIERS - SITE No. 3

FIGURE 12 - COMPLETED LIMESTONE BARRIERS - SITE No. 4

FIGURE 13 - COMPLETED LIMESTONE BARRIERS - SITE No. 5

FIGURE 14 - COMPLETED LIMESTONE BARRIERS - SITE No. 6

Table 6. CHEMICAL ANALYSIS OF CRUSHED LIMESTONE

Chemical Substance	Percent by Weight
Iron	0.10
Calcium Oxide	55.50
Magnesium Oxide	0.70
Loss on Ignition	42.15
Other	1.55
Calculated from CaO plus MgO	
Calcium Carbonate	99.06
Magnesium Carbonate	1.46

Table 7. SIEVE ANALYSIS OF CRUSHED LIMESTONE

Screen Size	Percent Passing
10.16 cm (4")	100
6.35 cm (2 1/2")	34

Construction Costs

On November 28, 1971 all work under the original contract was completed, and the total value of this work was $184,338.60. In February 1972 extra work was authorized at Site Nos. 1, 4, 5 and 6. The extra work included replacement of approximately 15.3 cu. meters of crushed limestone at Site No. 1, placement of some additional stone rip-rap on creek banks at Site Nos. 4 and 6 to help prevent bank erosion, and placement of heavy rocks and a 60.96 cm (24-inch) grout-filled corrugated metal pipe (placed approximately perpendicular to channel flow and sloped away from the creek bank) to act as a deflector and to help prevent scouring of the crushed limestone in the channel of Limestone Barrier No. 1-B at Site No. 1. The authorized extra work also included scarifying and redistributing the crushed limestone in the barrier at Site No. 5, where accumulated iron sludges had clogged the voids in the limestone materials and neutralization of the acid was not being effectuated. The total value of the extra work was $6,784.00; it was started in April 1972 and completed in May 1972.

Construction costs for the original project, together with costs for the extra work authorized in February 1972, are shown in Table 8, and include a breakdown of quantities of work and materials at the various sites.

Table 8. CONSTRUCTION COST - TROUGH CREEK LIMESTONE BARRIERS

Contract Item - Description	Unit	Quantities - Trough Creek Limestone Barrier Site No.						Total Quantity	Unit Price	Amount
		1	2	3	4	5	6			
Site Clearing (Lump Sum)									$15,000.00	$ 15,000.00
Excavation and Disposal	C.Y.	116	1,082	832	2,410	456	4,410	9,306	2.40	22,334.40
Rolled Embankment	C.Y.	80	- -	100	47	-	882	1,109	1.80	1,996.20
Rip Rap Creek Bank Linings	S.Y.	170	171	36	148	-	419	944	12.00	11,328.00
Grouted Stone Rip-Rap	S.Y.	82	137	164	169	43	203	798	18.00	14,364.00
Concrete Masonry	C.Y.	40.5	4	7	33	4	65	153.5	80.00	12,280.00
Rock Fills	C.Y.	175	269	220	332	15	90	1,577	12.00	18,924.00
12-Inch V.C. Channel Pipe	L.F.	-	-	-	-	25	-	25	20.00	500.00
18-Inch V.C. Channel Pipe	L.F.	-	-	-	25	-	-	25	24.00	600.00
24-Inch V.C. Pipe	L.F.	25	-	25	-	-	-	50	30.00	1,500.00
30-Inch V.C. Pipe	L.F.	-	-	-	138	-	276	414	18.00	7,452.00
24-Inch C.M. Pipe	L.F.	120	-	-	-	-	-	120	30.00	3,600.00
Crushed Limestone	C.Y.	531	188	334	539	688 •	1,076	3,356	24.00	80,544.00
								Total Value of Work		$190,422.60

• Prior to completion of the work the Contractor was authorized to scarify and redistribute the limestone materials at Site No. 5, as iron sludge began to accumulate, for a lump sum price of $700.00, bringing the total cost of work under the original contract to $191,122.60

SECTION VI

FLOOD DAMAGES - RECONDITIONING AND REPAIRS

GENERAL

In March 1972 heavy rainfall, accompanied by warm weather that melted deep snow in the Trough Creek Watershed, caused flooding at the limestone barrier sites. Local residents reported these flooding conditions to be the worst in many years in some areas. The spring flooding and high stream runoffs in March 1972 caused silting of the crushed limestone at Site Nos. 3, 4 and 6, and creek bank erosion was noted at Site Nos. 1, 3 and 6. Some scouring of the crushed limeston and displacement of rock fills occurred at Site Nos. 1, 2 and 3.

In late June 1972 severe flooding occurred throughout the watershed as a result of Tropical Storm Agnes. The extent of damages to the limestone barriers following the June flood was greater than that experienced in March, and included considerable silting of the crushed limestone beds, displacement of heavy rock fills at certain locations, creek bank erosion, and some scouring of the crushed limestone.

Presented below is a description of the effects of flooding at the various limestone barrier sites.

Site No. 1. High waters overflowed the horizontal concrete baffle in Barrier No. 1-B. Silting was noted at the lower end of the barrier, and some crushed limestone materials were scoured and deposited in the grouted stone rip-rap flume. Creek bank erosion occurred downstream from the flume.

Site No. 2. At Barrier No. 2-B the March 1972 flood caused debris build-up on the upstream side of barrier, some silting, but very little scouring of the limestone materials. At Barrier 2-A a few large stones were displaced on the downstream face of the barrier, and minor silting and some scouring of the limestone materials were noted following the March flood.

Damage resulting from the June flood at Site No. 2 included some movement of heavy rock fills, and the scouring and washing downstream of approximtely three-quarters of the limestone materials in Barrier No. 2-A, and approximately one-half of the limestone materials in Barrier No. 2-B. Also, considerable deposits of mud and gravel were noted immediately upstream from Barrier No. 2-B and the Rock Barrier. (See Figure 15)

FIGURE 15 - FLOOD DAMAGES - LIMESTONE BARRIERS - SITE No. 2

Site No. 3. The most extensive flood damage was experienced at this site, where the slope of the stream bed is steeper than at any of the other limestone barrier sites.

The March flood damages included displacement of a few large stones in the rock fills on the downstream faces of Barrier Nos. 3-A and 3-B, which are located in the main channel of Trough Creek. As a result, some scouring and washing downstream of the crushed limestone material occurred. Also, there was evidence of minor siltation of the limestone materials, and creek bank erosion was noted downstream from Barrier No. 3-A.

The magnitude of the June flood damages at Site No. 3 was greater than that experienced in March. At Limestone Barrier No. 3-A, nearly all the limestone materials were scoured and washed downstream, and approximately one-half of the heavy rock fills were displaced. Approximately three-quarters of Limestone Barrier No. 3-B was washed away, including the limestone materials and rock fills. The limestone materials in the approximate upper two-thirds of Limestone Barrier No. 3-C were scoured and washed downstream. (See Figure 16)

Site No. 4. The most serious effect of flooding at this site was siltation. The effects of both the March and June floods were similar, except that siltation following the June flood was more pronounced. Large quantities of mud and silt were deposited in the stilling basin upstream from the barriers, and also in the main channel downstream from the barriers. Silt deposits on the barriers and in the limestone filled channel area choked voids and prevented filtering action through the crushed limestone materials. (See Figure 17)

Site No. 5. There was no apparent damage to the barrier at this site from surface runoffs.

Site No. 6. Flood waters at this site caused silting of the barriers, stilling basin and stream channel similar to the conditions noted at Site No. 4, with the resultant clogging of voids in the crushed limestone materials. Approximately one-half of the limestone materials in Barrier No. 6-B were washed downstream during the June flood. There was no apparent scouring of the limestone materials during the March flood.

FIGURE 16 - FLOOD DAMAGES - LIMESTONE BARRIERS - SITE No. 3

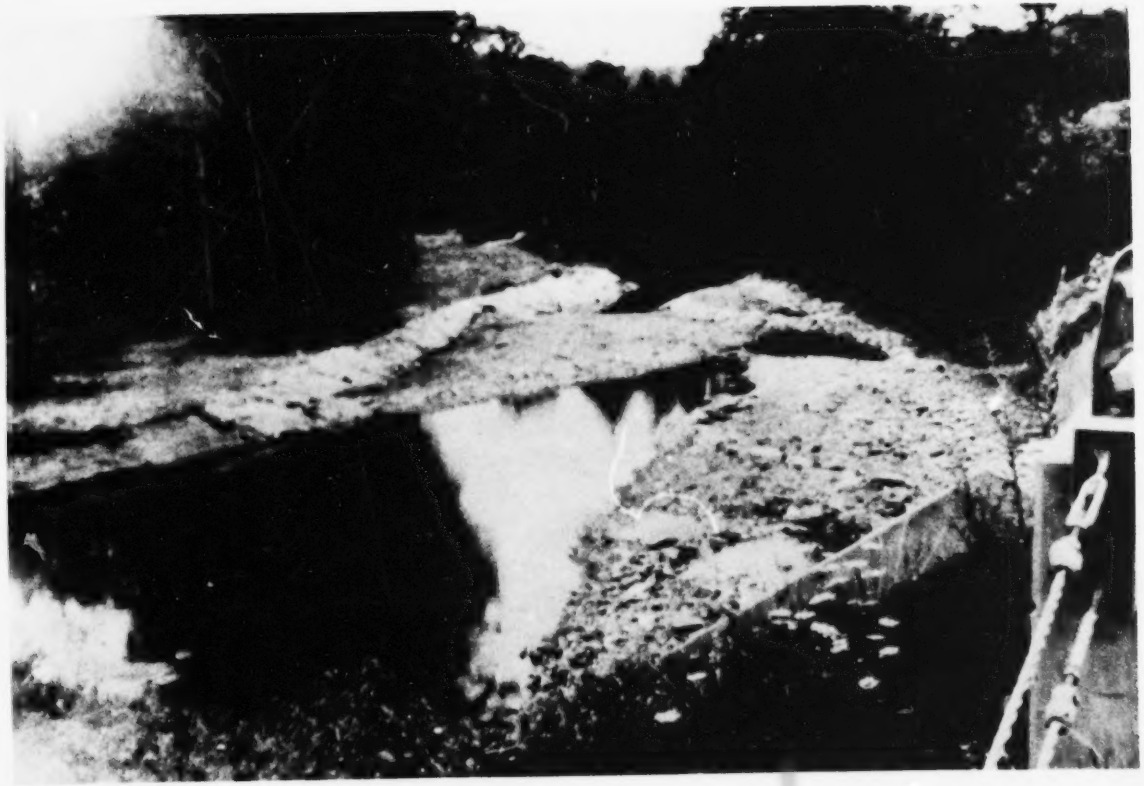

FIGURE 17 - FLOOD DAMAGES - LIMESTONE BARRIERS - SITE No. 4

Reconditioning and Repairs - Limestone Barriers

When flood waters receded in the Trough Creek Watershed following the June 1972 flood, an assessment of damages was made at each site to determine costs involved in restoring the limestone barriers to approximately original condition. The total estimated cost of construction for restoring the barriers at Site Nos. 1, 2, 3, 4 and 6 was $68,080.

In August 1972 the Commonwealth of Pennsylvania approved extra work expenditures under Contract No. SL-121-1 for restoring the limestone barriers at Site Nos. 1, 2 and 4. No additional work was authorized at Site Nos. 3 and 6. The restoration work at Site Nos. 1, 2 and 4 included excavation and disposal of mud and silt deposits, furnishing and placing rock fills on the downstream faces of barriers at Site No. 2 and in the channel at Site No. 4, furnishing and placing additional riprap creek bank linings at all three sites, rehandling and washing the crushed limestone materials remaining in the barriers to remove silt and restore the barriers to porous filtering beds, furnishing and placing new crushed limestone to replace materials washed away during the floods, and seeding ground surfaces adjacent to the barriers to help prevent soil erosion and washing. All work in connection with reconditioning and repairs of the limestone barriers was performed during periods of low stream flow.

The restoration work was started in late September 1972 and completed in early December 1972. A breakdown of quantities of work and materials at the various sites, together with unit costs for such work are shown in Table 9.

The procedures adopted for rehandling and washing the crushed limestone at each site were as follows:

1. Channels or drainage ways were excavated through the barriers parallel to streamflow between the downstream and upstream limits.

2. The silted limestone materials were excavated and stockpiled on each side of the drainage channels. Equipment used for this work was a combination dozer with a small backhoe and front-end loader.

3. The stockpiled silted limestone materials were rehandled, cleaned and washed with water under pressure, and replaced in final position in the barriers. A portable pumping unit that took suction from the stream was used for washing. This unit was a centrifugal pump with 3-inch suction and 3-inch discharge pipe connections, driven by a 12-horsepower gasoline engine, and delivered approximately 100 gallons per minute at a

corresponding total dynamic head of 100 feet. The end of the 3-inch discharge hose was equipped with a 1 1/2 inch steel pipe nozzle.

4. New crushed limestone was furnished and placed in the barriers to finished lines and grades to replace materials washed away during the floods.

Washing, and the placement of the crushed limestone materials in final position, was started at the upstream extremities of the barriers at each site and the operations progressed downstream so that sediment from washings would not clog or coat the surfaces of previously cleaned materials.

The reconditioning and repair work that was undertaken at Site Nos. 1, 2 and 4 after the June 1972 flood was successful in restoring these limestone barriers to porous filter bed structures, approximately equal in condition to that which existed when they were initially installed. The washing and rehandling operations thoroughly cleaned the crushed limestone rock surfaces that had become coated with clay-like materials and slimes, thus restoring the neutralizing ability of the carbonate rocks.

Table 9. RECONDITIONING AND REPAIR COSTS - LIMESTONE BARRIER FLOOD DAMAGES

Description	Unit	Quantities - Site No. 1	2	4	Total Quantity	Unit Price	Amount
Excavation	Cu. Yd.	20	455	515	990	$ 2.40	$ 2,376.00
Rip-Rap Creek Bank Lining	Sq. Yds.	25	290	130	445	12.00	5,340.00
Rock Fills	Cu. Yds.	8	95	115	218	12.00	2,616.00
New Crushed Limestone	Cu. Yds.	103	120	250	473	24.00	11,352.00
Rehandle and Wash Existing Crushed Limestone	Cu. Yds.	100	50	250	400	8.40*	3,360.00
Seed Ground Surfaces	Acre	0.23	-	0.25	0.48	2,000.00	960.00
					Total		$ 26,004.00

*The unit price of $8.40 per cubic yard for rehandling and washing silted crushed limestone that remained in the barriers after the floods was a negotiated price not included in the original contract, and represented 35 percent of the contract bid price for furnishing and installing new materials.

NOTE: To convert cubic yards (cu. yds.) to cubic meters, multiply cu. yds. x 0.7646
To convert square yards (sq. yds.) to square meters, multiply sq. yds. x 0.8361
To convert acre to hectare, multiply acre x 0.4047

SECTION VII

STREAM SAMPLING AND LIMESTONE ANALYSIS

GENERAL

Stream gaging and water sampling in connection with the evaluation of the performance of the Trough Creek Limestone Barriers was conducted on a monthly basis. This work was started prior to placement of any crushed limestone materials in the stream, and continued through the construction phase and for an additional period of time of approximately 17 months after completion of construction and flood damage repairs. Selected samples of limestone were placed in stainless steel containers in the barriers during construction, and were periodically removed, weighed and replaced. Electron microprobe and X-ray diffraction investigations were made on limestone samples to determine the chemical composition of deposits formed on the stones, and a determination was made of various algae and protozoan species mixed with the inorganic coating materials on the stones.

Eight (8) stream gaging stations were provided for measuring streamflow through the individual barriers, and fifteen (15) water sampling points were established. Figures 18 through 23 show the stream gaging stations and water sampling points at the various limestone barrier sites.

Stream Gaging

Streamflow was measured in gaging flumes of constant cross-section by the velocity-area method. Velocity was measured by a Gurley "Pigmy" current meter, except that a timed surface float was used under certain conditions when streamflow and depth of water was so low that meter readings appeared erratic.

During the construction phase of the Project, water samples were collected monthly at each of the six (6) limestone barrier sites. At the sites where gaging flumes were in place, streamflow was measured as noted above. However, at proposed downstream sites where gaging flumes had not been constructed, water samples were collected and streamflow was noted either "Estimated" or "Not Recorded." "Estimated" streamflow determinations were made either by surface float or current meter, where all streamflow appeared to be confined to stream sections where the velocity could be measured and the cross-sectional area reasonably determined. Where the pattern of streamflow was such that a reasonable estimate of flow could not be determined, it was noted "Not Recorded."

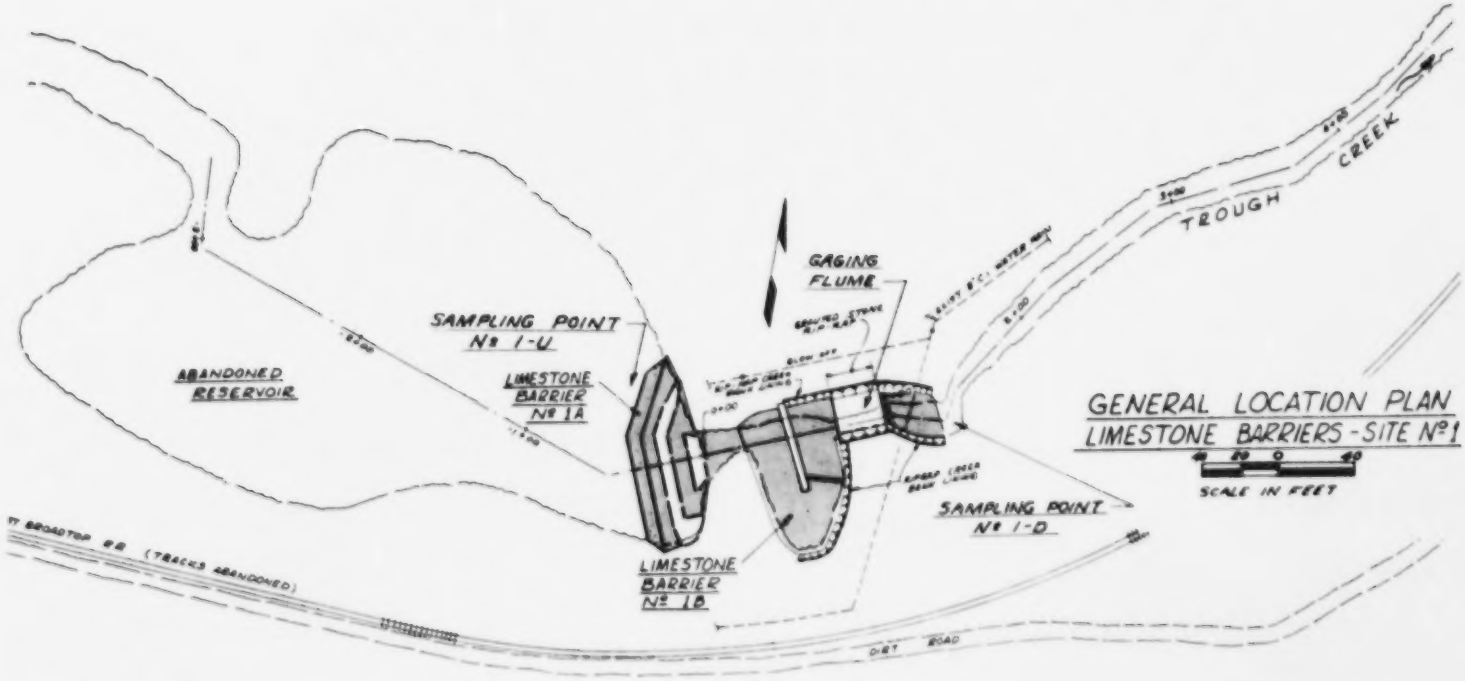

Figure 18. Sampling Points and Gaging Station — Site No. 1

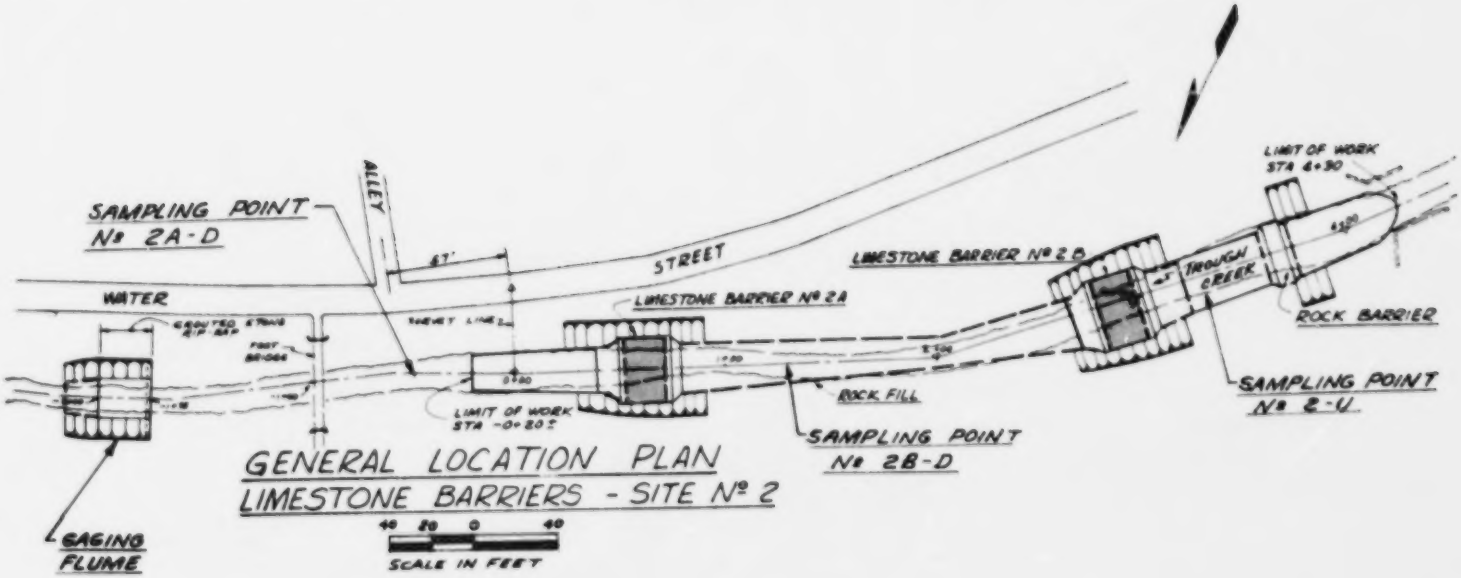

Figure 19. Sampling Points and Gaging Station — Site No. 2

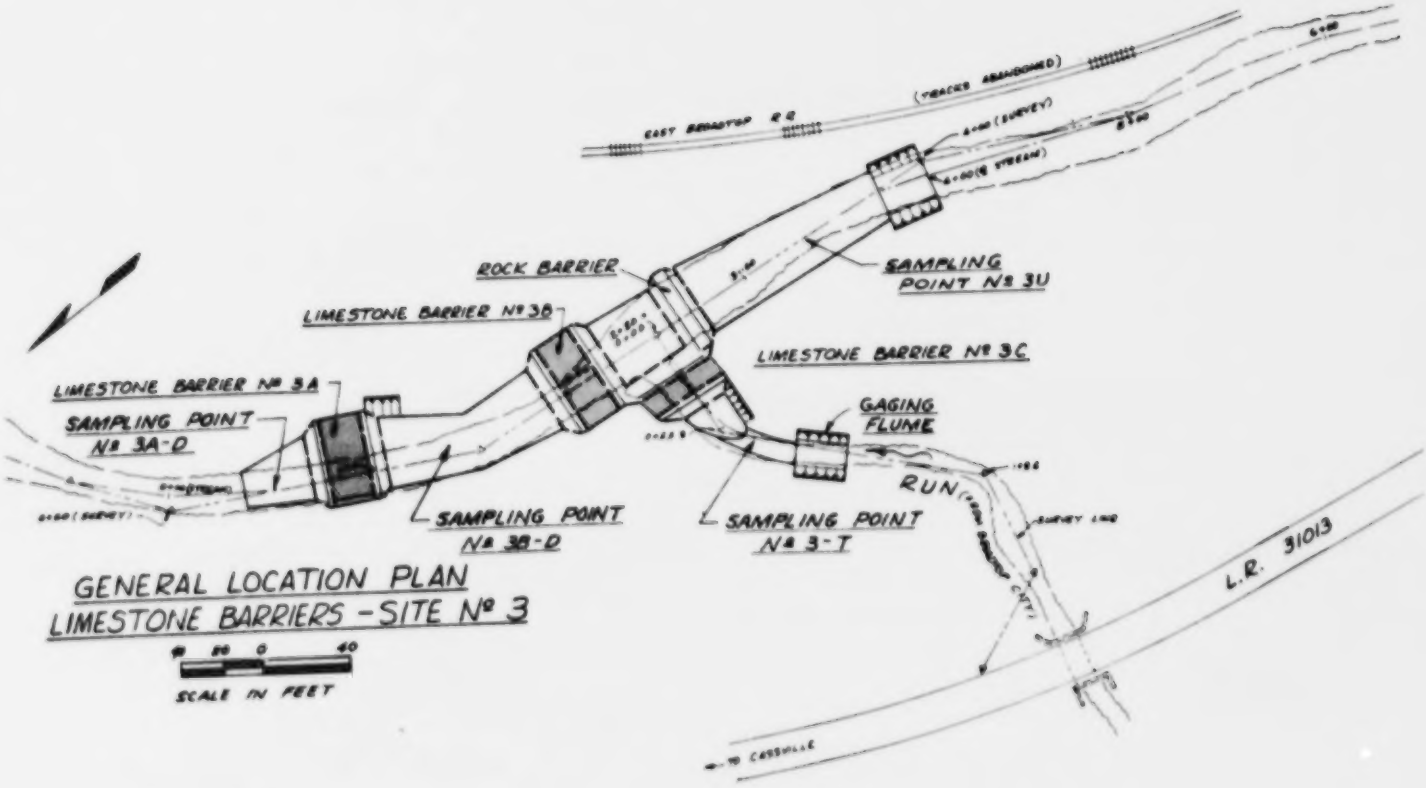

Figure 20. Sampling Points and Gaging Station — Site No. 3

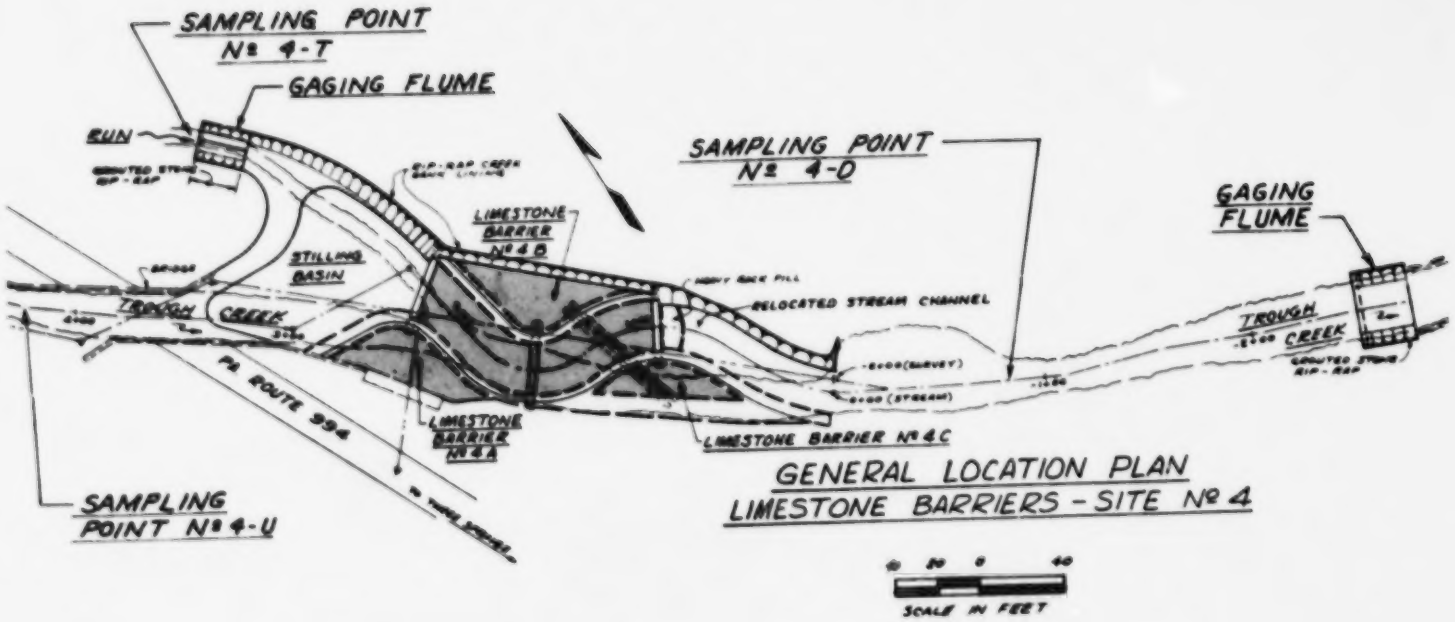

Figure 21. Sampling Points and Gaging Station — Site No. 4

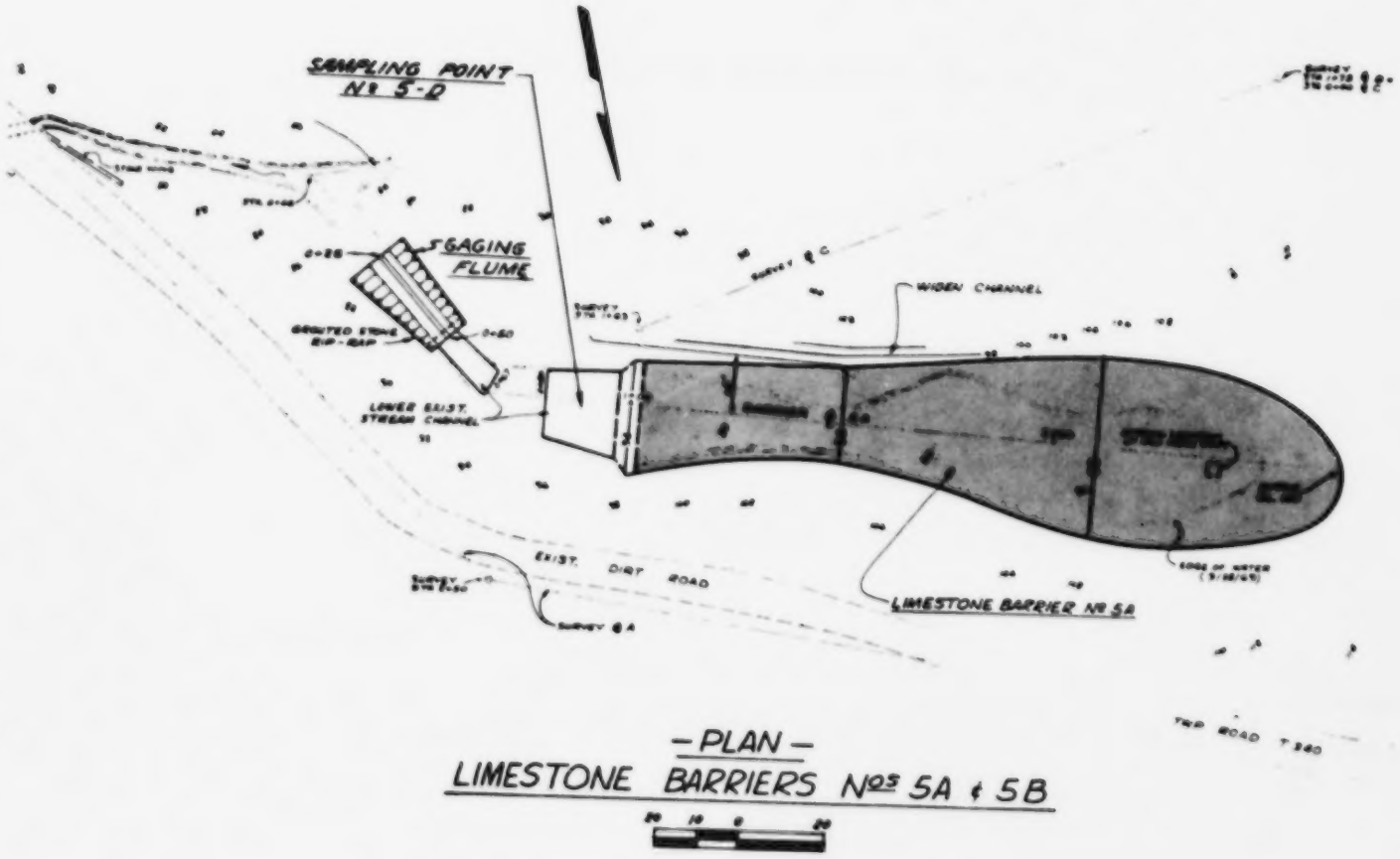

Figure 22. Sampling Points and Gaging Station — Site No. 5

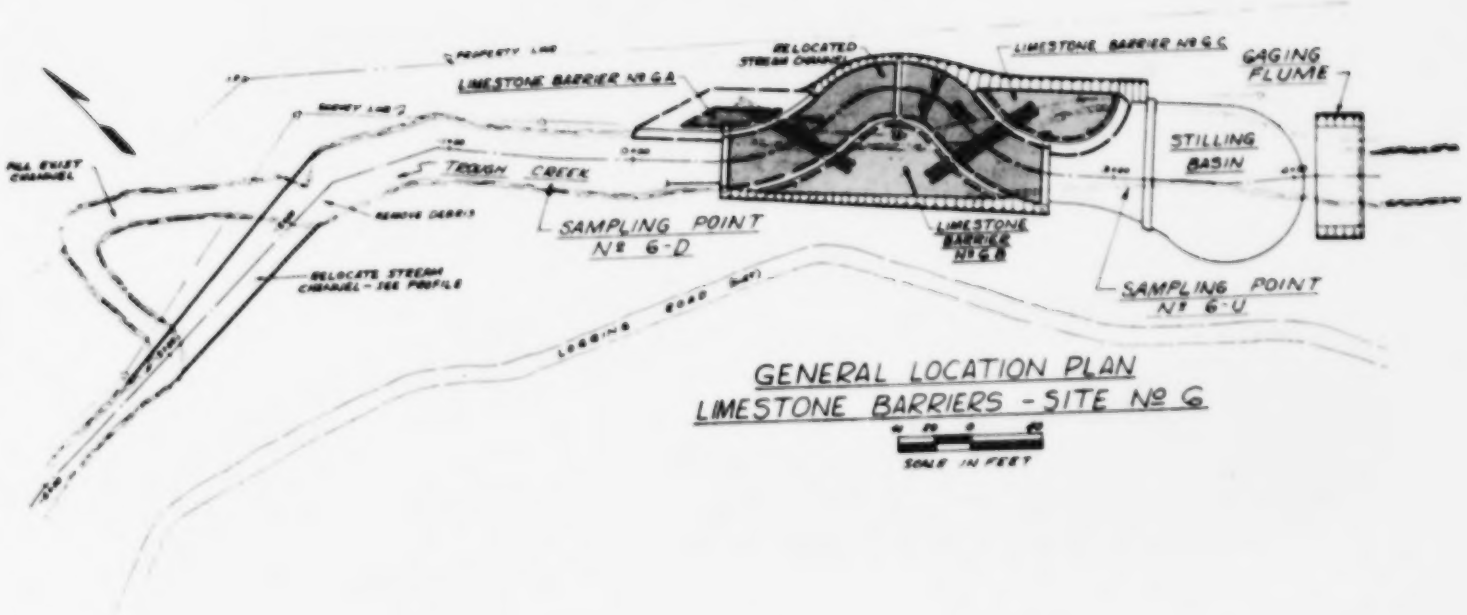

Figure 23. Sampling Points and Gaging Station — Site No. 6

Water Sampling

At each site, water samples were collected upstream and downstream from the individual barriers. The collected water samples were packaged and sent to testing laboratories designated by the Commonwealth of Pennsylvania. The water sample analysis consisted of determinations of pH, acidity, alkalinity, sulfates and iron. The testing laboratories were under contract with the Commonwealth for performing such services, and throughout the course of this sampling program, four separate laboratories conducted the chemical analyses.

During the construction phase of the Project, only one monthly sample was collected in the main stream and tributary at uncompleted limestone barrier sites. As previously mentioned, restoration work was undertaken at Limestone Barrier Site Nos. 1, 2 and 4 to repair 1972 flood damages. Although the barriers at Site Nos. 3 and 6 were not included in the authorized restoration work, water samples were collected and analyzed at these sites for the full sampling program period. When it became obvious that barrier performance at Site No. 5 was no longer effective because iron sludges had coated rock surfaces and clogged voids in the crushed limestone materials, water sampling at this site was discontinued.

A complete tabulation of the results of analysis of water samples collected during the study period is presented in the Appendix. Figures 24 through 29 show a plotting of pH values at the various sites, upstream and downstream from the barriers. These figures also show the rate of stream flow at the time of sample collection, and the sequence of construction of the limestone barriers.

As previously noted, iron concentrations were generally less than 1 milligram per liter at all sampling points, except at Site No. 5. The results of the sampling program are discussed in SECTION VII.

Limestone Analysis

The limestone analysis phase of the sampling program to evaluate the effectiveness of the Trough Creek Limestone Barriers consisted of placing selected samples of limestone in the barriers in 22.86 cm x 22.86 cm x 22.86 cm (9" x 9" x 9") stainless steel baskets. The baskets were of welded construction and were fabricated from 2.54 cm x 2.54 cm x 0.32 cm (1" x 1" x 1/8") angle frames and 0.305 cm (0.120") wire screens. Wires for screens were spaced 2.54 cm (1") center to center both ways. Twelve baskets (two at each limestone barrier site) were installed in the barriers in 1971 and 1972 following completion of the work under the original construction project. Initially it was intended that the baskets be removed from the barriers at each site at three month intervals and be

analyzed for:

(a) Loss of weight as a factor of time and flow
(b) Tendency for deposits to form on the limestone
(c) Chemical composition of any deposits

In this connection, vandalism was a problem at Site Nos. 1 and 2, and some of the baskets at other sites were washed away or damaged during the March and June 1972 floods. Of the original twelve baskets that were installed in the barriers only four baskets were recovered which, upon loss of weight analysis, appeared to provide reasonably accurate data. These baskets were subsequently placed in the barriers at Site Nos. 1, 2 and 4 following completion of flood restoration work in late 1972.

The schedule for removal and replacement of limestone filled baskets at three month intervals could not be strictly adhered to, because it was not possible or practical under certain conditions due to the nature of streamflow in Trough Creek. The baskets had to be placed near the bottom of the barriers to insure that they would be submerged during periods of low stream flow. Installation of the baskets during average or high streamflow would have required the use of heavy construction equipment, which could have damaged the baskets and abraded the stones during installation and/or removal, thus increasing the probability of error in the loss of weight analysis.

Usually when baskets were removed from the barriers for sampling, silt deposits, ranging from light to severe, were present in the voids of the limestone pieces. The limestone samples in each basket were washed with clean water, scrubbed lightly with a soft fiber brush, dried, weighed and then returned to the barriers. Tables 10 through 13 show loss of weight of the limestone samples in the four baskets that were preserved and protected during the study period.

A review of the limestone analysis indicates that the rate of loss-of-weight (percent per year) fluctuated over a wide range. This variation is attributed to the fact that sediment deposits clogged interstices between the stones, thus inhibiting free stream flow through the baskets and lessening the opportunity for reaction of the limestone with flowing acidic water. This matter is discussed in detail in SECTION VIII. Although the average rate of limestone consumption appeared to be in the neighborhood of 3 to 5 percent per year, it would be ill-advised to attempt to predict the life of the limestone barriers on the basis of the results of this loss-of-weight analysis.

Table 10. LIMESTONE ANALYSIS - BASKET NO. 2

Date Installed (I) / Date Removed (R)		Weight (Kg)	Loss of Weight (Kg)	Time (Days)	Rate of Loss of Weight (% per year)	Cumulative Loss of Weight (Kg)	Total Elapsed Time (Days)
2/10/71	(I)	12.474	0.474	358	3.874	0.474	358
2/3/72	(R)	12.0					
2/8/72	(I)	12.0	0.013	351	0.112	0.487	709
1/24/73	(R)	11.987					
2/8/73	(I)	11.987	0.212	183	3.528	0.699	892
8/10/73	(R)	11.775					
8/21/73	(I)	11.775	0.123	111	3.436	0.822	1,003
12/13/73	(R)	11.652					
1/3/74	(I)	11.652	0.193	126	4.797	1.015	1,129
5/10/74	(R)	11.459					
5/23/74	(I)	11.459	0.100	70	4.552	1.115	1,199
8/2/74	(R)	11.359					

Table 11. LIMESTONE ANALYSIS - BASKET NO. 6

Date Installed (I) / Date Removed (R)		Weight (Kg)	Loss of Weight (Kg)	Time (Days)	Rate of Loss of Weight (% per year)	Cumulative Loss of Weight (Kg)	Total Elapsed Time (Days)
2/8/72	(I)	12.5	0.122	100	3.562	0.122	100
5/18/72	(R)	12.378					
6/20/73	(I)	12.378	0.279	176	4.674	0.401	276
12/13/73	(R)	12.099					
1/3/74	(I)	12.099	0.098	126	2.346	0.499	402
5/10/74	(R)	12.001					
5/23/74	(I)	12.001	0.165	70	7.170	0.664	472
8/2/74	(R)	11.836					

Table 12. LIMESTONE ANALYSIS – BASKET NO. 8

Date Installed / Date Removed	(I) (R)	Weight (Kg)	Loss of Weight (Kg)	Time (Days)	Rate of Loss of Weight (% per year)	Cumulative Loss of Weight (Kg)	Total Elapsed Time (Days)
2/8/72	(I)	12.9	0.025	100	0.708	0.025	100
5/18/72	(R)	12.875					
1/24/73	(I)	12.875	0.325	323	2.852	0.350	423
12/13/73	(R)	12.555					
1/3/74	(I)	12.555	0.173	126	3.992	0.523	549
5/10/74	(R)	12.382					
5/23/74	(I)	12.382	0.273	70	11.498	0.796	619
8/2/74	(R)	12.109					

Table 13. LIMESTONE ANALYSIS – BASKET NO. 9

Date Installed / Date Removed	(I) (R)	Weight (Kg)	Loss of Weight (Kg)	Time (Days)	Rate of Loss of Weight (% per year)	Cumulative Loss of Weight (Kg)	Total Elapsed Time (Days)
2/8/72	(I)	11.4	0.212	351	1.934	0.212	351
1/24/73	(R)	11.188					
2/8/73	(I)	11.188	0.316	183	5.633	0.528	534
8/10/73	(R)	10.872					
8/21/73	(I)	10.872	0.200	111	6.050	0.728	645
12/13/73	(R)	10.672					
1/3/74	(I)	10.672	0.202	126	5.484	0.930	771
5/10/74	(R)	10.470					
5/23/74	(I)	10.470	0.164	70	8.166	1.094	841
8/2/74	(R)	10.306					

Limestone Coatings

After the barriers were in service for some time, the coatings on surfaces of the crushed limestone materials were examined for chemical composition and biological growth. The Pennsylvania Fish Commission collected stone samples in July 1971 at Site Nos. 1, 2 and 3. They found that the material coating the limestone at each site contained a significant amount of inorganic materials. Attached to and mixed with this material were various forms of algae and protozoan species. At the time of the Fish Commission sampling the barriers at Site No. 1 had been in service for approximately 9 months, at Site No. 2 for approximately 6 months, and at Site No. 3 for approximately 3 months. The results of the biological survey were as follows:

Site No. 1 - Diatoms and protozoans abundant in the film coating the limestone.
Site No. 2 - Diatoms replaced by filamentous algae which were abundant. Protozoans were reduced in number and diversity.
Site No. 3 - Film consisted primarily of inorganic materials, with very few protozoans or algae forms present.

Deposits on limestone samples collected from the barriers were also examined and anlyzed by X-ray diffraction, and later by electron microprobe to determine elements present in the coating materials. In July 1972 the coatings from limestone samples collected from each limestone barrier site (six total) were scraped off and subjected to X-ray diffraction analysis. All samples showed poor crystallinity, making phase identification difficult. The materials that were identified were calcite (from the limestone), quartz and gypsum. Visually it could be seen that iron oxides were present in the rock coatings, but since the X-ray patterns did not show the presence of any iron compounds, they were assumed to be amorphous (amorphous or non-crystalline materials will not give an X-ray diffraction pattern, hence cannot be identified by this technique).

In November 1972 an electron microprobe investigation was made of the deposits on limestone samples collected from the barriers at Site. Nos. 2, 3 and 5. Two wavelength scans were made of the deposits on these samples, and the analysis showed the following elements present:

Site No. 2 - Silicon, Potassium, Aluminum, Iron
Site No. 3 - Aluminum, Silicon, Titanium, Potassium, Calcium, Iron
Site No. 5 - Calcium, Aluminum, Iron, Silicon, Potassium, Sulfur

One wavelength scan was made of a limestone sample collected from the

barrier at Site No. 1. The coating deposits on the surface of this stone were removed prior to analysis, and the investigation of this sample did not show any elements being absorbed.

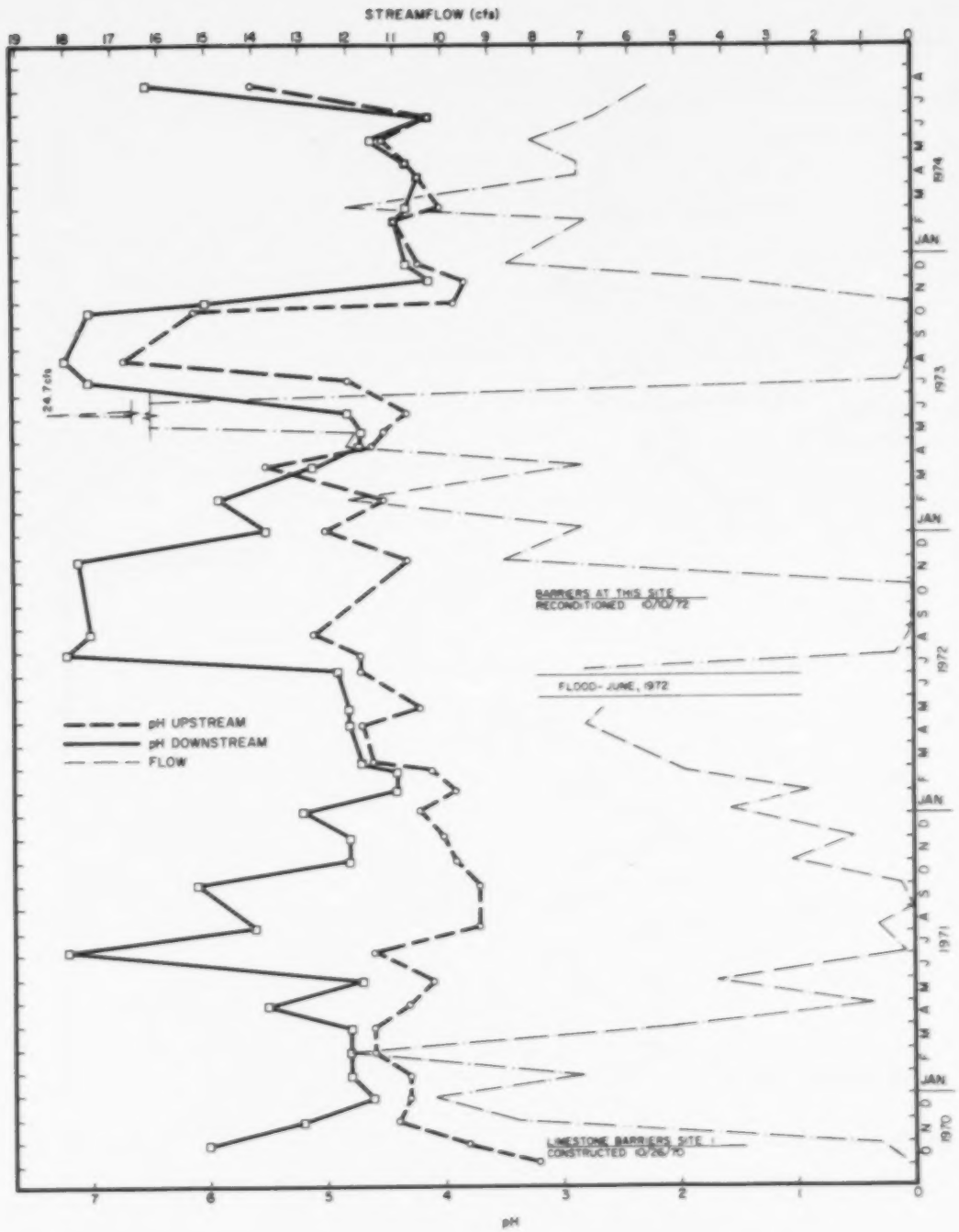
STREAMFLOW (cfs)
19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
24.7 cfs
BARRIERS AT THIS SITE RECONDITIONED 10/10/72
FLOOD- JUNE, 1972
LIMESTONE BARRIERS SITE I CONSTRUCTED 10/26/70
pH UPSTREAM
pH DOWNSTREAM
FLOW
7 6 5 4 3 2 1 0
pH
O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A
1970
JAN
1971
JAN
1972
JAN
1973
JAN
1974

Figure 24. Performance of Limestone Barriers—Site No. I

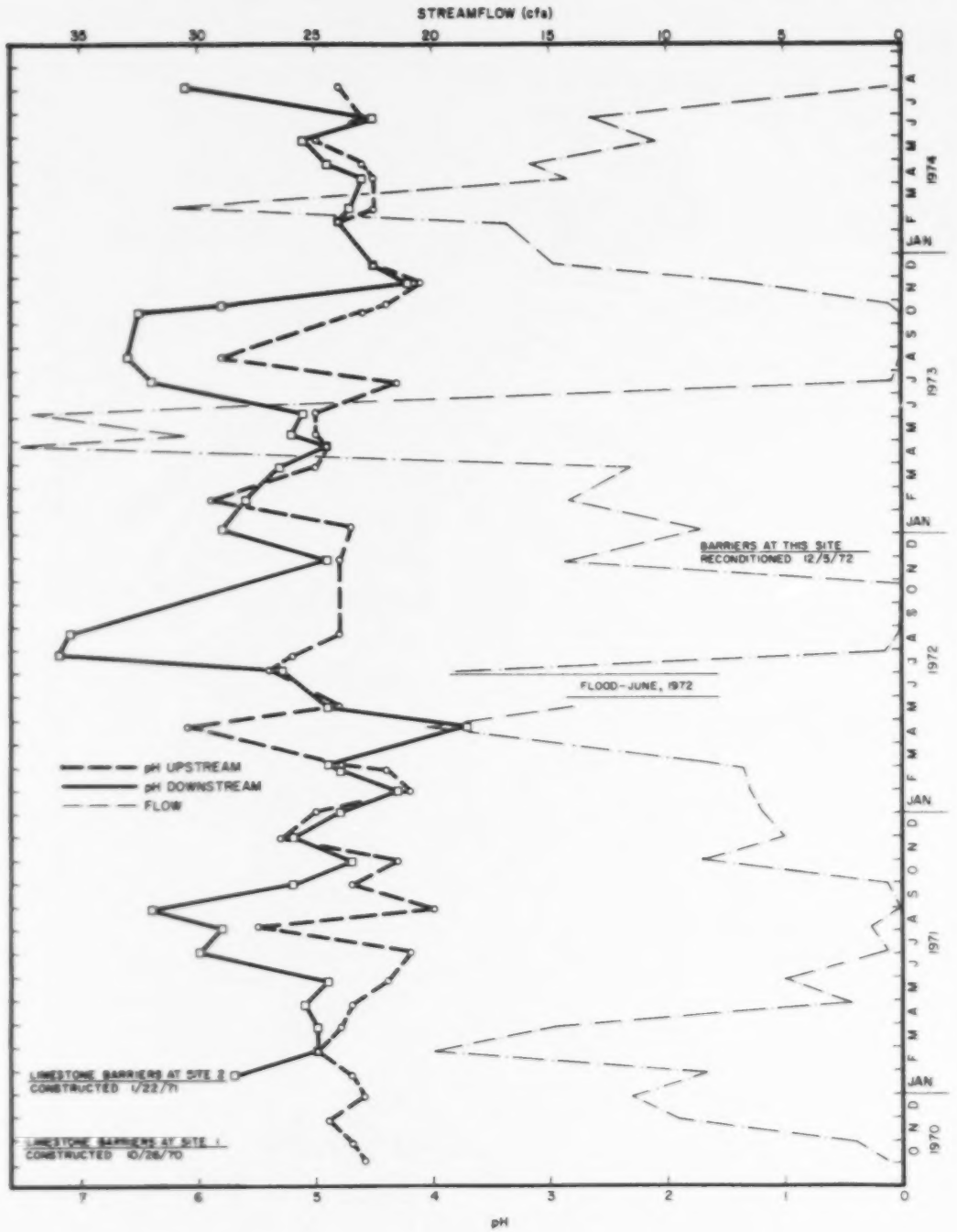

Figure 25. Performance of Limestone Barriers — Site No. 2

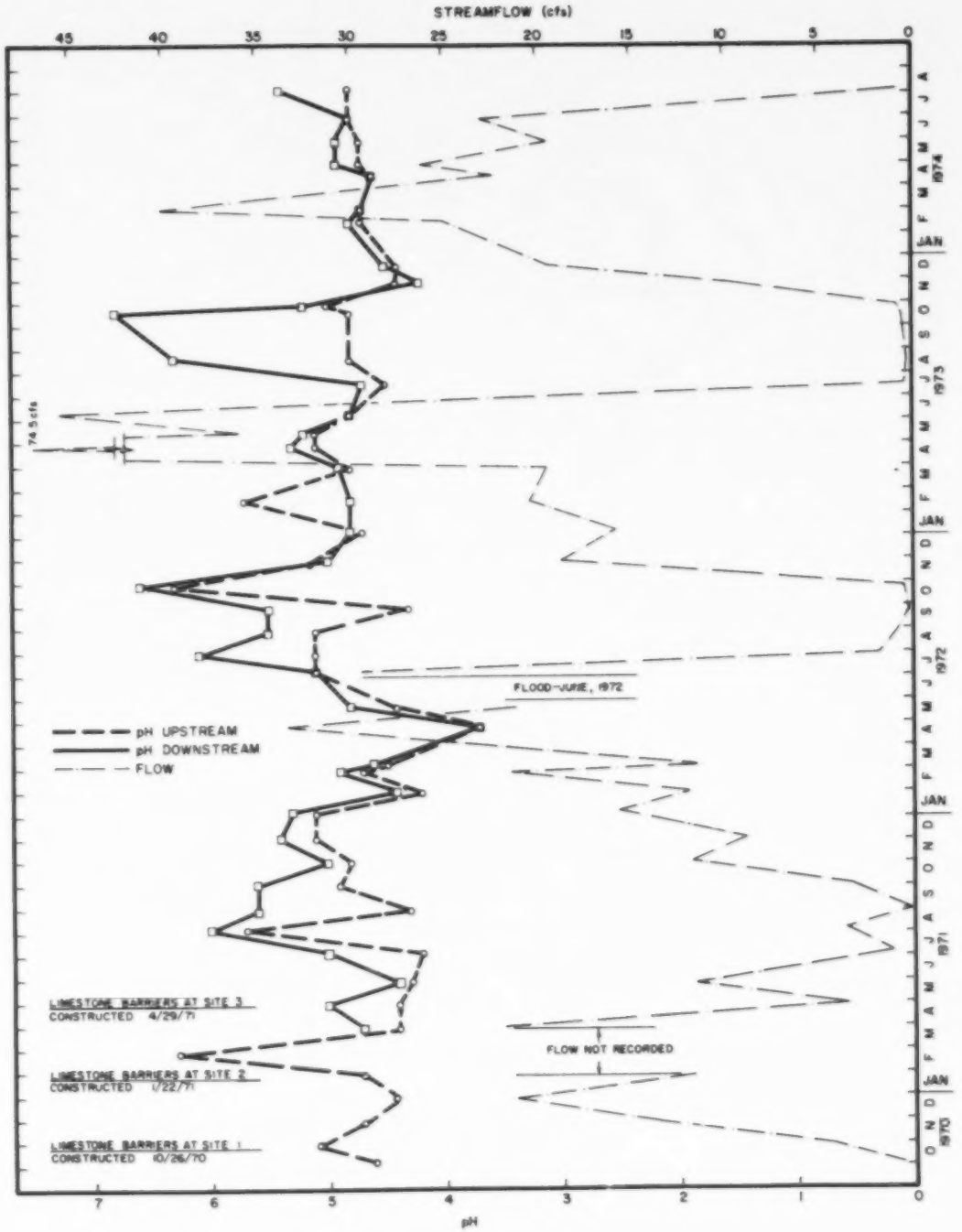

Figure 26. Performance of Limestone Barriers—Site No. 3

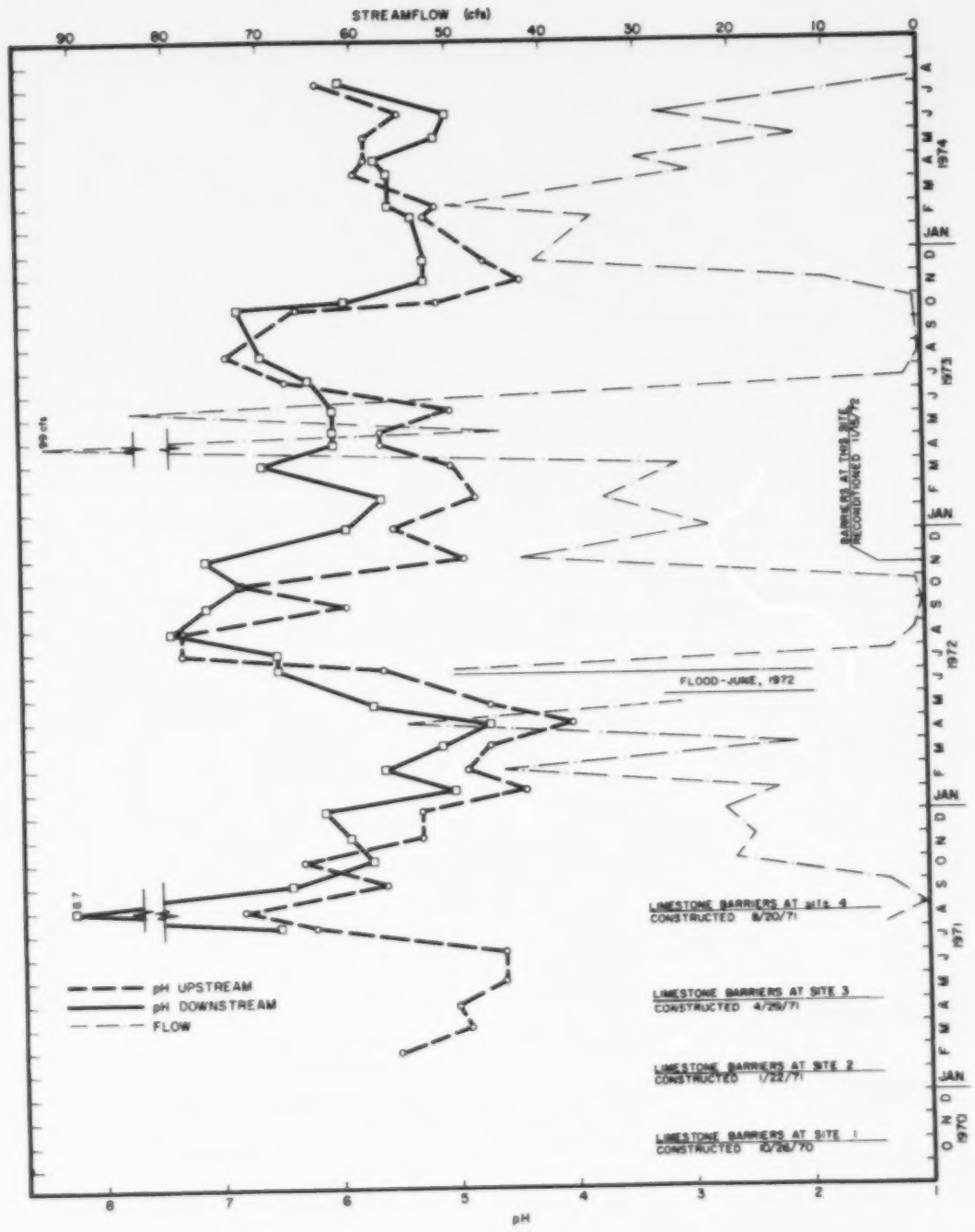

Figure 27. Performance of Limestone Barriers—Site No. 4

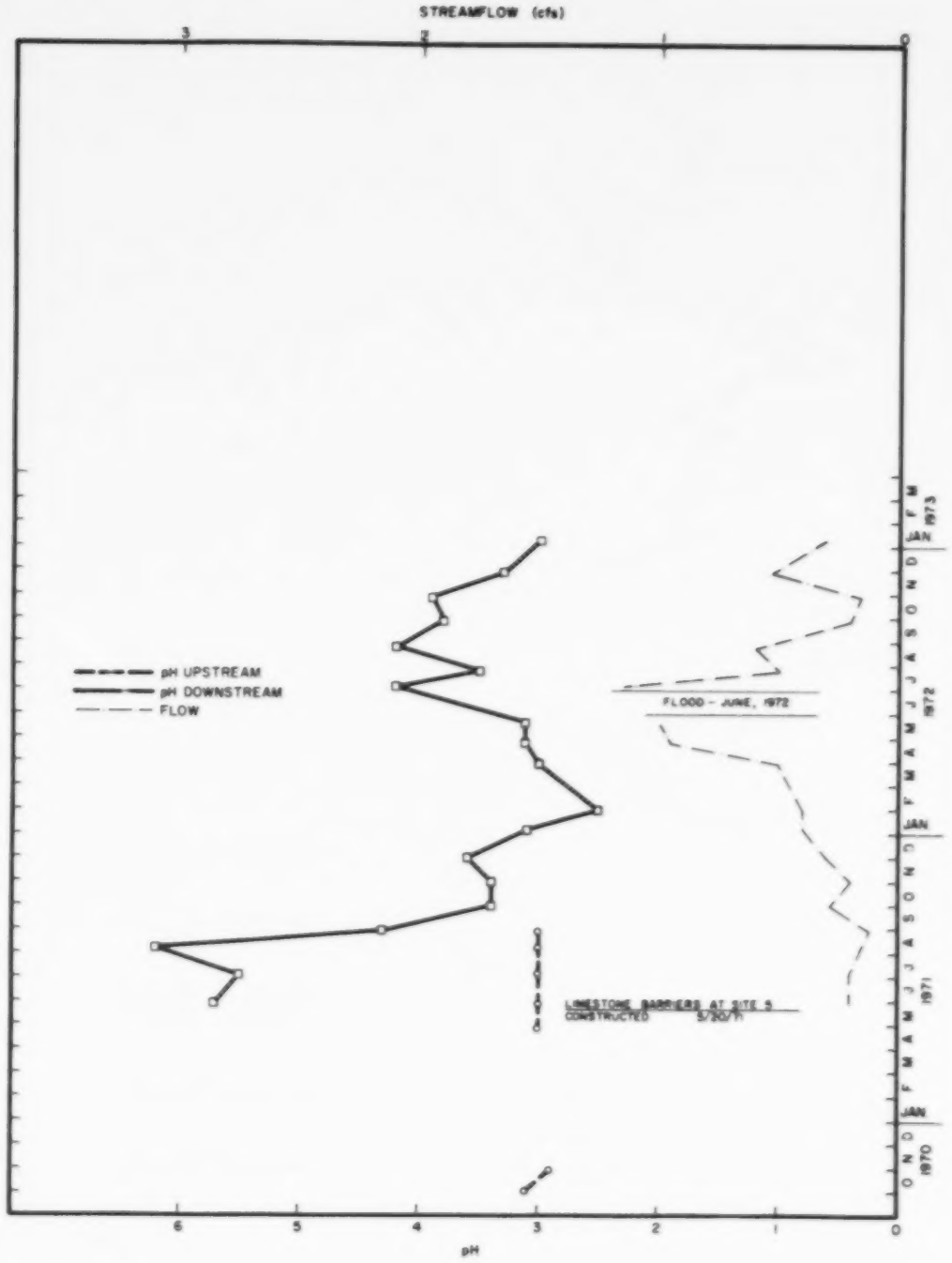

Figure 28. Performance of Limestone Barriers—Site No. 5

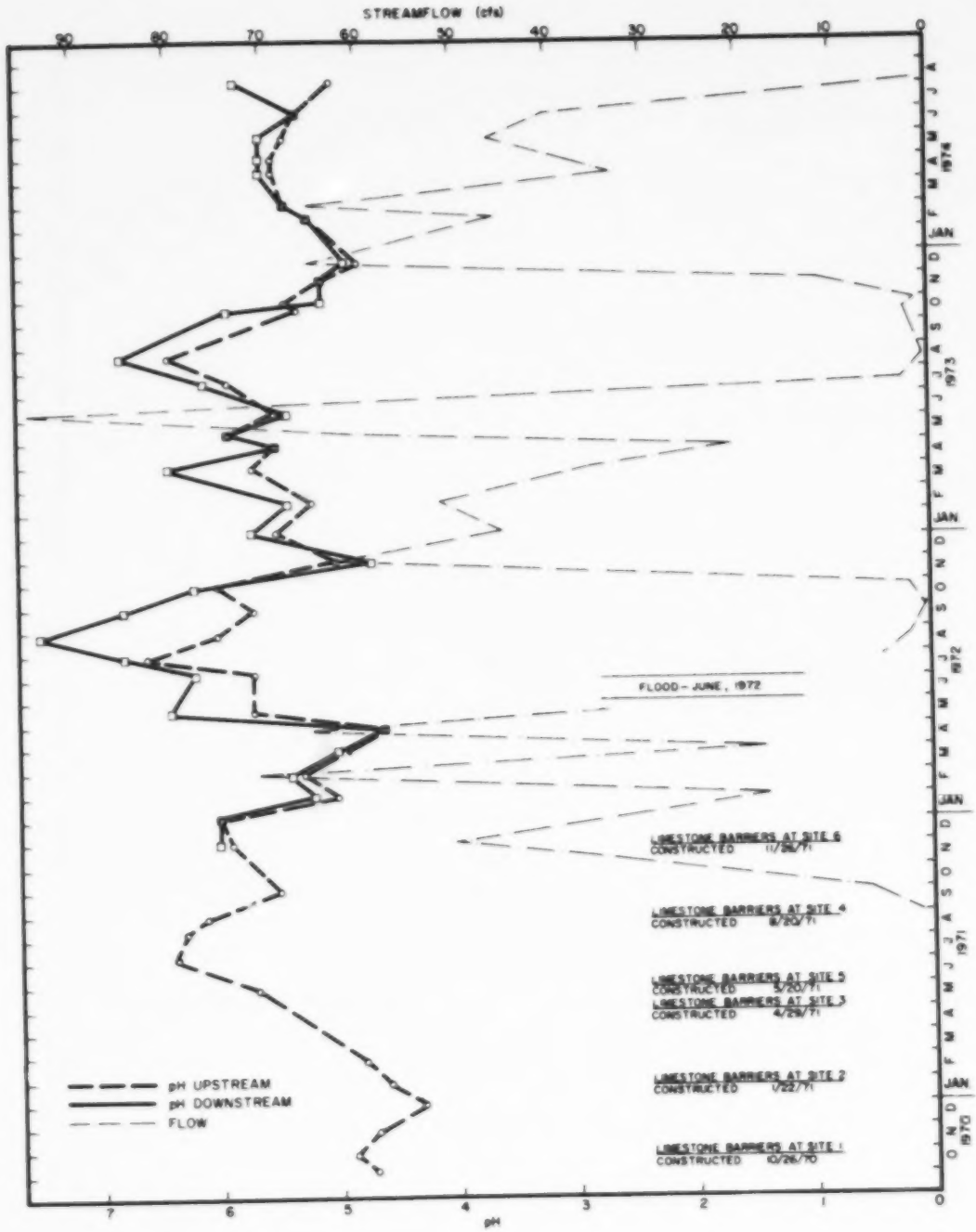

Figure 29. Performance of Limestone Barriers—Site No. 6

SECTION VIII

LIMESTONE BARRIER PERFORMANCE

GENERAL

The performance of six Trough Creek prototype limestone barrier installations was observed during and after the construction phase of the project for the period extending from October 1970, when the first barrier was erected, to August 1974. Information gathered throughout the sampling program period, together with observations noted in the field, made it possible to evaluate the effectiveness of in situ limestone barriers over a wide range of stream conditions. The field observations and the data collected during the sampling program also provided useful information in evaluating the extent to which design relationships used for this project, that were developed from laboratory research, could be supported.

It is apparent from even a cursory examination of the results of the stream sampling program that the limestone barriers, as constructed, were not successful in providing workable facilities satisfactory for area-wide abatement of pollution from acid mine drainage in the upper reaches of the Trough Creek Watershed. Although barrier performance was excellent during periods of low stream flow, in terms of reducing acidity and raising the pH of the water, their effectiveness was marginal at design flows, and they were completely ineffective when high runoffs were experienced. Also, it is apparent from a review of the results of the stream sampling program that limestone barriers are most efficient when they are initially installed, or after they have been otherwise restored by reconditioning and repair work similar to that undertaken following the 1972 flood. For the Trough Creek Project, limestone barrier performance deteriorated after the the structures had been in service for some time following initial construction, and again after the barriers had been reconditioned following flood damage restoration work.

Deterioration of Limestone Barrier Performance

The rate of deterioration of limestone barrier performance is apparently dependent upon two major factors; namely, siltation and coating of the surfaces of the stones. The most serious cause of barrier deterioration for the Trough Creek Project appeared to be sealing of the crushed limestone materials, whereby sediment accumulations of either silt or iron sludges clogged interstices between the stones. The result of such clogging not only reduces the effective porosity and hydraulic conductivity of the crushed limestone beds, but also lessens availability of the reagent (limestone) to flowing acidic water.

When limestone barriers are initially constructed, or after they have been reconditioned, almost all of the limestone materials are available for neutralization. However, after sediment deposits begin to accumulate and clog voids in the limestone materials, the streamflow pattern through a barrier begins to channel, causing short-circuiting of the flow and the resultant reduction in retention time. The hydraulic capacity of limestone barriers likewise diminishes as silt deposits accumulate, because the permeability of clogged or partially clogged beds becomes substantially reduced.

The other factor that causes deterioration of the performance of limestone barriers is coating of the surfaces of the stones with silt or iron hydroxides. During periods of turbid or muddy streamflow, silt collects on the surfaces of the stones. The effect of coating of the stones is a buffering action that effects a reduction in the neutralizing ability of the limestone. Although the silt coatings are easily removed physically by washing, they do not have a tendency to wash or flake off in the stream. Rather, they tend to build up over a period of time, depending on stream conditions, and progressively lessen limestone reactivity. It was also found that during the warmer months of the year algae growths were mixed with the inorganic coating materials.

For the Trough Creek Project, the combined effect of coating of the surfaces of the stones and sealing of the beds was that deterioration of the performance of the limestone barriers was experienced within a few months after initial construction, and again after reconditioning. It should be noted, however, that except where the surfaces of the stones become armored with iron hydroxides, the upper layer of limestone appears to remain effective, because the barriers continued to neutralize acidity when stream flow was very low.

General Observations - Silting of Limestone Barriers

Where limestone barriers are to be installed to neutralize acidity in streams subject to severe flooding and a wide variation of flow, acknowledgment must be made of the fact that sediment deposits will tend to clog voids in the crushed limestone materials and stone surfaces will become coated with silt. In this connection, the following observations were noted for the Trough Creek Project:

1. Silting, and the resultant clogging of voids of limestone materials, is more pronounced during the first year after installation, because: (a) existing stream beds and streamflow patterns were altered, and (b) vegetation and natural ground cover adjacent to the structures was disturbed and/or destroyed during the construction operations, thus increasing the possibility of soil erosion from surrounding areas.

2. Where limestone barriers are constructed in areas where the slope of the stream bed is steep, such as at Site No. 3, consideration should be given to lining both the creek banks and channel with rocks for the entire reach of stream to prevent erosion, and also the placement of large stones in the channel area approaches to disrupt and disperse streamflow patterns.

3. Stream channel approaches to the limestone barrier sites should include provisions for dissipating the kinetic energy of stream flow. The work under the Trough Creek Project included construction of grouted stone rip-rap flumes at each site for the purpose of measuring the rate of stream flow during the sampling program. At Site Nos. 3, 4 and 6 the flumes were installed upstream from the barriers and provided a straight, fairly smooth channeled water course of constant cross-section with invert elevations higher than what was expected to be normal water level. During periods of high runoffs the streamflow through the flumes approaches scouring velocity, and apparently stirs and churns previously settled mud and silt in the stilling basin areas, carrying these materials onto the barriers.

Concurrent Studies - Trough Creek Limestone Barriers

In November 1972, the Institute For Research On Land And Water Resources at The Pennsylvania State University initiated additional research relative to the reactivity of limestone with acid mine waters. [3] This research work was undertaken after the limestone barriers at Site No. 1, 2 and 4 had been substantially restored to approximate original condition following damages experienced as a result of the June 1972 flood. The water sampling and analysis portion of the University study was conducted concurrently with the sampling program under this evaluation project; however, the chemical analysis and the laboratory testing procedures at the University were considerably more comprehensive in scope.

The University Study concluded basically that limestone barriers can be used effectively to neutralize acid waters if they are designed properly and if the iron concentrations are sufficiently low. The study indicated that the proper design was found to depend very heavily on the reduction of reactivity of the limestone due to deposits of silt and precipitates which may have formed. For the barriers in Trough Creek this reactivity was found to have apparently decreased five-fold from limestone reactivity monitored under clean conditions in the University laboratory.

As a consequence of this University study, a set of design graphs was generated which incorporate the reduction in limestone reactivity so that the designer can take this factor into account and build the system sufficiently large to overcome this deficiency. The University concluded

that even with the increased volume requirement, limestone barriers appear to provide a reasonably economical solution for neutralization of acid waters under conditions of low iron concentrations.

Evaluation - Limestone Barriers

The undertaking of construction of the Trough Creek Limestone Barrier Installation Project was the first such endeavor for in-stream treatment of acid mine drainage for an entire watershed where the range of streamflow was of the magnitude of Trough Creek. The design relationships used for this prototype project were developed from laboratory research in the late 1960's at The Pennsylvania State University. Presented below are evaluations of the design relationships based on the experiences of the performance of the Trough Creek Limestone Barriers. These evaluations are based on results of the sampling program and field observations noted during the study period October 1970 to August 1974.

1. The performance of the limestone barriers, in terms of reducing acidity and raising the pH of the water, did not reach theoretical efficiency, except for a short period of time at Site No. 5. A possible explanation for the reason they did not reach theoretical efficiency is that the design relationships for reduction of acidity were formulated from laboratory experiements using synthetic acid waters of both 50 and 100 mg/l initial acidity; whereas, initial stream acidities (upstream from the barriers) for the Trough Creek Project were only in the neighborhood of 10 to 20 mg/l, except at Site No. 5 where initial acidity was approximately 150 to 200 mg/l. If initial acidity in the stream had been somewhat higher, the percent reduction of acidity may have been greater.

2. Limestone barrier performance was more efficient for the long, continuous barriers at Site Nos. 1, 4 and 5 than it was for the short, multiple barriers at Site Nos. 2 and 3. The laboratory research thesis postulated that acidity reduction is proportional to the total length of the barrier, without regard to whether it is an integrated long structure or comprised of segregated short units. At Site Nos. 2 and 3 two short barriers, approximately 7.6 meters (25 feet) in length, were positioned in series in the main channel of the stream. At Site Nos. 1 and 4 the barriers were interconnected with shallow limestone fills and the barrier at Site No. 5 consisted of a single structure. The limestone fill areas for the barriers at Site Nos. 1, 4 and 5 were all in excess of 45.7 meters (150 feet) in length.

3. The performance of the limestone barrier at Site No. 5 was excellent after completion of initial construction. The characteristics of the raw acid mine drainage at this Site were approximately 150 to 200 mg/l acidity and 30 mg/l (total) iron. Within a period of approximately three months the performance of this barrier, for all practical purposes, completely deteriorated because of accumulations of iron sludges in the limestone bed and armoring of the surfaces of the stones with iron hydroxides.

4. Initial performance of the limestone barriers was good at all other sites (Nos. 1, 2, 3, 4 and 6), where iron concentrations of the water were approximately 1 mg/l or less, but performance also deteriorated to a considerable degree after a few months following completion of construction. This deterioration is attributed to sediment accumulations sealing the limestone beds and also coating of the surfaces of the stones with silt. This condition was discussed in detail previously in this SECTION.

5. The performance of silted limestone barriers can be restored to approximate initial efficiency by performing reconditioning work similar to the procedures adopted for flood damage repairs at Site Nos. 1, 2 and 4.

6. It was difficult to attempt to assess the accuracy of hydraulic design relationships regarding head losses, stone size and flow through the barriers, because sediment deposits accumulated in a short period of time following completion of construction, causing "dead spots" in the barriers and channelling flow through indeterminate areas. However, the head loss relationships seemed to be confirmed by observations noted over a limited range of streamflow during the short period of time the barriers were in clean condition.

7. Although the research thesis recommended the use of small stone sizes for the crushed limestone materials, consideration must be given to the magnitude of high runoffs and flood flows that might occur that will cause scouring of the materials. For the Trough Creek Project a considerable degree of scouring was experienced, even though the larger stone sizes (6.35 cm to 10.16 cm, or 2 1/2" to 4") were used in the barriers.

Comments Regarding Future Limestone Barrier Design

On the basis of the conditions experienced with the Trough Creek limestone barriers, it is apparent that the design of such units must take into account the effect of deteriorating barrier performance caused by siltation and coating of the surfaces of the stones. The five-fold reduction in limestone reactivity noted in the recent Pennsylvania State University research study would appear to provide an ample factor of safety for design. Likewise, it seems apparent that in the design of limestone barriers, the size of the units should be determined from design flows greater than those used for this project. (Design flows for Trough Creek Limestone Barriers were 1.25 times computed average flow.) A considerable portion of the Trough Creek Project watershed consists of wooded lands, some farms, and other areas where acid mine drainage would not be generated from surface runoffs. Originally, it was believed that ample dilution of stream acidity would be afforded during periods of high surface runoff from these areas. The results of the sampling program indicate that a more realistic value for design flow would appear to be approximately 300 percent of computed average streamflow, depending on watershed conditions.

Barrier configuration will naturally depend to a certain degree on topography of the areas adjacent to proposed structures. However, barrier performance will probably be more efficient if the units are long, continuous structures, flat and relatively shallow (approximately 1 meter or 3 feet in depth or less), and constructed in areas where adequate hydraulic gradient is available under all conditions of streamflow.

It is evident that a maintenance program should be established to periodically recondition limestone barriers so that performance will not deteriorate beyond required efficiencies. The scheduling and extent of such maintenance work would be dependent on local conditions and watershed runoff characteristics.

A reasonable estimate of the life of properly operated limestone barriers could not be determined from the limestone loss of weight analysis, because of the siltation problems noted in SECTION VII. However, with the excess volume of limestone needed to compensate for reduction in limestone reactivity, together with the larger structures required to accomodate high design flows, the amount of crushed limestone materials that would be furnished for properly sized units would undoubtedly provide ample reagent for many years.

In view of the deficiencies in performance of the limestone barriers on the Trough Creek Project, it is questionable whether it is feasible to attempt to provide in-stream limestone barriers exclusively as the treatment method for area-wide mine drainage pollution abatement, even

though the chemical characteristics of the acid waters appear suitable to treatment with limestone. Rather, it is believed that construction of limestone barriers in conjunction with other watershed improvements, such as backfilling strip mined areas, replanting and possibly some mine sealing, would be a more practical approach to regional mine drainage pollution abatement where the watershed areas and runoff characteristics are similar to those of Trough Creek.

SECTION IX

REFERENCES

1. Yen, Alan Fong - I, Design of Limestone Barriers in Acid Mine Water Streams, A Thesis in Civil Engineering, The Pennsylvania State University, University Park, September, 1969.

2. Africa Engineering Associates, Inc., details reproduced from Plans for Contract No. SL-121-1, Construction of Limestone Barriers - Trough Creek Watershed - Huntingdon and Bedford Counties, Pa., prepared for Department of Mines and Mineral Industries, Commonwealth of Pennsylvania, by Africa Engineering Associates, Inc., Consulting Engineers, Huntingdon, Pa., 1970.

3. Pearson, F. H. and McDonnell, A. J., "Neutralization of Acidic Wastes by Crushed Limestone, "Research Publication No. 79, and "Evaluation of Prototype Crushed Limestone Barriers for the Neutralization of Acidic Streams," Research Publication Number 80, Institute for Research on Land and Water Resources, The Pennsylvania State University, University Park, Pennsylvania, June, 1974.

SECTION X

APPENDIX

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COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF ENVIRONMENTAL RESOURCES
BUREAU OF PLANNING AND COAL RESEARCH

TROUGH CREEK LIMESTONE BARRIER INSTALLATION AND EVALUATION
PROJECT NO. 14010 - FWW
CR-105

KEY TO SYMBOLS USED IN REPORTING RESULTS OF WATER ANALYSIS AND SAMPLE COLLECTIONS

*	Estimated stream flow. Accurate measurements of Stream Flow were not made until grouted rip-rap measuring flumes were constructed.
N.R.	Stream Flow not Recorded. Flow pattern of stream was such that a reasonable estimate of the rate of flow could not be made at time of sample collection.
--	Values not reported by Testing Laboratory.

SEQUENCE OF CONSTRUCTION – LIMESTONE BARRIERS

Site No.	Date Started	Date Completed
1	July 27, 1970	October 26, 1970
2	October 27, 1970	January 22, 1971
3	January 25, 1971	April 29, 1971
4	May 20, 1971	August 20, 1971
5	May 3, 1971	May 20, 1971
6	August 20, 1971	November 26, 1971
(Extra Work) Change Order No. 1 1, 4, 5, 6	April, 1972	May 15, 1972
(Extra Work) Change Order No. 2 1, 2, 4	September 26, 1972	December 5, 1972

NOTE: To convert cubic feet per second (cfs) to m^3/s; multiply cfs x 0.02832

SHEET I WATER ANALYSIS - SITE NO. 1

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Sampling Date	Flow (cfs)	pH		Acidity (mg/l)		Alkalinity (mg/l)		SO_4 (mg/l)		Iron (mg/l)			
										1-U		1-D	
		1-U	1-D	1-U	1-D	1-U	1-D	1-U	1-D	Total	Ferrous	Total	Ferrous
10/2/70	0.25*	3.8		32		0		105		0.55			
10/28/70	0.84	3.8	6.0	32	4	--	8	70	--	6.25		0.7	
11/27/70	8.4	4.4	5.2	6	0	0	0	--	--	0.25		1.65	
12/30/70	10.2	4.3	4.6	8	10	--	0	24	28	1.7		5.25	
1/26/71	7.0	4.3	4.8	8	4	0	0	32	100	3.3		0.35	
2/26/71	12.0	4.6	4.8	0	0	0	4	32	20	0.35	0	0.7	0
3/30/71	5.0	4.6	4.8	10	12	--	--	28	28	0.1	0	0.1	0
4/28/71	0.84	4.3	5.5	12	8	--	0	36	28	0.55	0	0.35	0
5/28/71	4.2	4.1	4.7	0.6	--	--	6	40	28	0.1	0	0.1	0
7/2/71	0.13	4.6	7.2	--	--	4	44	44	80	0.1	0	1.1	0
9/5/71	0.78	3.7	5.6	22	0	--	0	75	75	6.0	0	4.2	0
8/31/71	0.00	Samples not collected - no flow											
10/1/71	0.26	3.7	6.1	22	--	--	8	95	75	0.3	0	0.1	0
11/1/71	2.6	3.9	4.8	6	0	--	0	40	30	0.1	0	0.1	0
12/1/71	1.26	4.0	4.8	4	0	--	0	24	18	0.1	0	0.1	0
1/4/72	3.9	4.2	5.2	4	--	--	6	44	48	0.1	0	0.1	0
2/1/72	2.2	3.9	4.4	8	6	--	--	38	40	0.1	0	0.1	0
2/28/72	4.9	4.1	4.4	4	2	--	--	44	40	0.1	0	0.1	0

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(Con't) SHEET II WATER ANALYSIS - SITE NO. 1

Sampling Date	Flow (cfs)	pH		Acidity (mg/l)		Alkalinity (mg/l)		SO_4 (mg/l)		Iron (mg/l)			
										1-U		1-D	
		1-U	1-D	1-U	1-D	1-U	1-D	1-U	1-D	Total	Ferrous	Total	Ferrous
3/31/72	N.R.	4.6	4.7	9	25	2	3	20	25	0.21	0.12	0.23	0.12
4/25/72	7.0	4.7	4.8	8	7	2	2	24	26	0.32	0.08	0.34	0.13
5/18/72	6.6	4.2	4.8	8	11	--	--	21	25	0.33	0.06	0.44	0.06
7/5/72	7.*	4.7	4.9	12	10	--	--	29	30	0.47	0.06	0.36	0.03
7/24/72	0.4	4.9	7.2	14	8	--	--	24	26	0.33	0.06	0.65	0.03
8/22/72	0.05*	5.1	7.0	16	15	2	45	31	37	0.52	- --	0.52	- --
9/26/72	0.00	Samples not collected - no flow											
10/26/72	0.00	"	"	"	"	"							
11/30/72	8.7	4.3	7.1	11	9	0	18	27.5	29	0.20	0.02	0.19	0.02
1/8/73	7.0	5.0	5.5	3	7	9	12	22.5	25	0.21	0.08	0.14	0.08
2/15/73	12.0	4.5	5.9	7	8	0	0	24	17	0.2	<0.2	<0.1	<0.1
3/30/73	7.0	5.5	5.1	3	5	0	0	20	20	<0.1	- --	<0.1	- --
4/23/73	12.0	4.6	4.7	9	6	0	0	22	24	<0.1	- --	<0.1	- --
5/10/73	11.8	4.5	4.7	8	10	0	0	26	26	0.2	<0.2	0.2	<0.2
6/7/73	24.7	4.6	4.8	10	5	0	0	22	24	<0.1	<0.1	<0.1	<0.1
7/16/73	0.3	4.8	7.0	8	0	0	20	29	24	<0.1	- --	0.1	- --
8/17/73	trickle	6.7	7.2	0	0	0	52	24	26	0.6	- --	0.5	- --
10/16/73	trickle	6.1	7.0	0	0	0	40	26	36	<0.1	- --	0.1	- --
10/24/73	0.4	3.9	6.0	18	10	0	10	40	60	0	- --	0	- --

(Con't) SHEET III WATER ANALYSIS - SITE NO. 1

TROUGH CREEK LIMESTONE BARRIER INSTALLATION AND EVALUATION
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CR-105

Sampling Date	Flow (cfs)	pH		Acidity (mg/l)		Alkalinity (mg/l)		SO_4 (mg/l) (mg/l)		Iron (mg/l)			
										1-U		1-D	
		1-U	1-D	1-U	1-D	1-U	1-D	1-U	1-D	Total	Ferrous	Total	Ferrous
11/23/73	3.7	3.8	4.1	8	10	0	0	35	33	0.146	- --	0.146	- --
12/19/73	8.6	4.2	4.3	4	2	0	0	23	22	0.146	- --	0.146	- --
2/14/74	6.9	4.4	4.4	6	6	0	0	20	21	0.146	- --	0	- --
3/1/74	12.0	4.0	4.3	4	8	0	0	26	27	0	- --	0	- --
4/11/74	7.1	4.2	4.2	6	6	0	0	45	35	0	- --	0	- --
4/30/74	7.1	4.3	4.3	6	6	0	0	23	26	0	- --	0	- --
5/28/74	8.1	4.5	4.6	2	2	0	0	27	26	0	- --	0	- --
6/27/74	6.7	4.1	4.1	10	10	0	0	26	24	0	- --	0	- --
8/5/74	Trickle	5.6	6.5	8	6	12	82	26	30	0	- --	0	- --

SHEET I

WATER ANALYSIS - SITE NO. 2

TROUGH CREEK LIMESTONE BARRIER INSTALLATION AND EVALUATION
PROJECT NO. 14010 - FWQ
CR-105

Sampling Date	Flow (cfs)	pH			Acidity (mg/l)			Alkalinity (mg/l)			SO_4 (mg/l)			Iron (mg/l)					
														2-U		2B-D		2A-D	
		2-U	2B-D	2A-D	2-U	2B-D	2A-D	2-U	2B-D	2A-D	2-U	2B-D	2A-D	Total	Ferrous	Total	Ferrous	Total	Ferrous
10/2/70	0.65e	4.6			16			0			68			0.45					
10/28/70	2.0	4.7			8			4			--			2.1					
11/27/70	9.6	4.9			10			0			--			0.2					
12/30/70	11.6	4.6			10			0			26			0.4					
1/26/71	8.4	4.7	4.6	5.7	0	0	2	0	0	0	20	28	28	1.25		0.35		0.4	
2/26/71	20.0	5.0	5.0	5.0	4	4	16	0	0	0	22	24	32	1.0	0.4	0.2	0	0.2	0
3/30/71	14.8	4.8	5.0	5.0	8	8	8	--	--	--	28	24	32	0.1	0	0.1	0	0.1	0
4/28/71	2.1	4.7		5.1	2		4	0		0	36		24	0.3	0			0.45	0
5/28/71	5.0	4.4	4.6	4.9	4	--	0	--	6	0	24	32	32	0.1	0	0.2	0	0.1	0
7/2/71	0.6	4.2	4.7	6.0	8	0	--	--	0	6	42	70	60	0.1	0	1.4	0	0.5	0
8/5/71	1.35	5.5	5.4	5.8	0	0	--	0	0	4	44	38	54	0.6	0	1.1	0	0.6	0
8/31/71	0.01	4.0	6.3	6.4	12	--	--	--	10	22	60	70	85	1.1	0	5.5	0	2.0	0
10/1/71	0.61	4.7	4.8	5.2	0	10	--	0	--	4	75	75	40	0.1	0	0.1	0	0.1	0
11/1/71	8.5	4.3	4.7	4.7	6	4	8	--	--	--	30	42	22	2.2	0.1	0.1	0	0.1	0
12/1/71	5.0	5.3	5.2	5.2	0	2	--	0	--	10	30	24	38	1.0	0	0.1	0	0.1	0
1/4/72	6	5.0	5.1	4.8	--	--	--	2	4	2	28	48	38	0.1	0	0.1	0	0.1	0
2/1/72	6.5	4.2	4.1	4.3	4	6	4	--	--	--	48	40	40	0.1	0	0.3	0	0.1	0
2/28/72	6.8	4.4	4.8	4.8	2	--	--	--	18	18	40	40	28	0.1	0	0.3	0	0.1	0
3/31/72	8.1	4.8	4.6	4.9	7	8	6	1	1	2	30	23	28	0.19	0.12	0.19	0.08	0.09	0.02
4/25/72	20.3	6.1	3.9	3.7	6	10	12	4	0	0	21	26	28	0.36	0.13	0.26	0.12	0.20	0.03
5/18/72	14.0	4.8	4.9	4.9	5	6	4	--	--	--	23	24	17	0.30	0.12	0.41	0.10	0.32	0.08
7/5/72	19.3	5.4	5.4	5.3	5	6	6	--	--	--	27	27	27	0.26	0.06	0.24	0.06	0.23	0.03
7/24/72	0.7	5.2	5.8	7.2	22	9	9	--	--	--	29.5	29	31	2.88	0.03	0.32	0.03	0.23	0.03
8/22/72	0.06	4.8	6.1	6.9	20	27	19	1	16	34	47	--	--	0.23	--	0.83	--	0.75	--

(Con't) SHEET II WATER ANALYSIS - SITE NO. 2

Sampling Date	Flow (cfs)	pH			Acidity (mg/l)			Alkalinity (mg/l)			SO_4 (mg/l)			Iron (mg/l) 2-U		2B-D		2A-D	
		2-U	2B-D	2A-D	2-U	2B-D	2A-D	2-U	2B-D	2A-D	2-U	2B-D	2A-D	Total	Ferrous	Total	Ferrous	Total	Ferrous
9/26/72	Samples not collected - no flow																		
10/26/72	Samples not collected - no flow																		
11/30/72	14.3	4.8	4.9	4.9	6	5	4	1	2	2	23	23.5	23	0.18	0.02	0.21	0.02	0.16	0.03
1/8/73	8.6	4.7	6.5	5.8	6	4	2	2	14	9	22	21	21	0.10	0.03	0.12	0.08	0.16	0.08
2/15/73	14.8	5.9	5.0	5.6	7	6	3	0	0	0	17	17	17	0.1	<0.1	0.1	<0.1	0.2	<0.2
3/30/73	11.5	5.0	5.2	5.3	8	4	4	0	0	0	15	10	20	<0.1	- --	0.3	- --	<0.1	- --
4/23/73	37.5	4.9	5.0	4.9	4	4	8	0	0	0	12	19	17	<0.1	- --	<0.1	- --	<0.1	- --
5/10/73	30.5	5.0	5.1	5.2	8	8	4	0	0	0	31	24	14	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
6/7/73	37.1	5.0	5.1	5.1	8	6	6	0	0	0	26	29	36	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
7/16/73	0.4	4.3	6.8	6.4	8	0	0	0	0	0	38	34	34	<0.1	- --	<0.1	- --	0.1	- --
8/17/73	trickle	6.8	6.2	6.6	0	0	0	30	18	14	53	58	46	1.0	- --	0.5	- --	0.2	- --
10/16/73	trickle	4.6	6.9	6.5	6	0	0	0	32	36	43	48	50	<0.1	- --	0.5	- --	<0.1	- --
10/24/73	0.5	4.4	5.8	5.8	10	10	10	2	4	10	35	40	35	0	- --	0	- --	0.146	- --
11/23/73	6.8	4.1	4.1	4.2	8	8	10	0	0	0	32	27	30	0.146	- --	0	- --	0.146	- --
12/19/73	14.8	4.5	4.6	4.5	4	4	2	0	2	0	26	20	20	0	- --	0.146	- --	0	- --
2/14/74	16.9	4.8	4.8	4.8	2	4	2	2	4	6	19	19	19	0	- --	0	- --	0.146	- --
3/1/74	31.0	4.5	4.6	4.7	4	2	4	0	2	2	24	22	23	0	- --	0	- --	0	- --
4/11/74	14.2	4.5	4.8	4.6	4	4	4	0	2	4	30	45	30	0	- --	0	- --	0	- --
4/30/74	15.8	4.6	4.9	4.9	4	4	2	2	4	4	24	21	18	0	- --	0	- --	0	- --
5/28/74	10.5	5.0	5.0	5.1	2	2	2	6	6	4	23	26	24	0	- --	0	- --	0	- --
6/27/74	13.3	4.6	4.5	4.5	8	6	8	2	0	0	24	20	20	0	- --	0	- --	0	- --
8/5/74	0.5	4.8	6.2	6.2	10	6	8	4	42	44	36	38	39	0.1	- --	0.3	- --	0	- --

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SHEET I WATER ANALYSIS - SITE NO. 3

Sampling Date	Flow (cfs)	pH				Acidity (mg/l)				Alkalinity (mg/l)				SO_4 (mg/l)				Iron (mg/l)							
																		3-U		3-T		3B-D		3A-D	
		3-U	3-T	3B-D	3A-D	3-U	3-T	3B-D	3A-D	3-U	3-T	3B-D	3A-D	3-U	3-T	3B-D	3A-D	Total	Ferrous	Total	Ferrous	Total	Ferrous	Total	Ferrous
10/2/70	1.0 * 0.6 ◆ 1.6 *	4.7	4.6		4.6	0	10		10	90	--			72	44		48	0.35		0.55				0.1	
10/28/70	2.9 * 1.5 ◆	5.1	4.9			4	6			4				--	12			8		0.1					
11/27/70	12.5 * 1.2 * 13.7 *	4.6	4.8		4.7	16	10		0( )	0	0		0	--	--		--	0.25		0.2				0.4	
12/30/70	18.3 * 3.0 * 21.3 *	4.3	4.8		4.4	4	4		6	0	0		0	36	12		22	0.4		1.2				0.8	
1/26/71	10.7 * 1.0 * 11.7 *	4.8	4.9		4.7	4	0		0	0	0		0	36	20		32	0.55		0.8				1.9	
2/26/71	N.R. N.R.		5.0		6.3		2		0		0		2		28		22			0.25				0.25	
3/30/71	18.0 * 3.9 * 21.9 *	4.4	4.8		4.7	4	10		14	--	--			24	28		24	0.1		0.1				0.1	
4/28/71	3.75 0.65 4.4	4.4	4.8		5.0	6	6		0	0	0		0	28	24		40	0.3	0	0.6	0			0.4	0
5/28/71	6.7 4.9 11.6	4.3	4.6	4.4	4.4	4	--	4	4	--	6	--	--	28	38	48	40	0.2	0	0.1	0	0.2	0	0.3	0
7/2/71	0.75 0.31 1.06	4.2	4.6	4.6	5.0	10	2	0	0	--	--	0	0	80	28	60	80	0.1	0	0.1	0	0.4	0	0.4	0
8/5/71	2.65 0.98 3.63	5.7	4.4	5.5	6.0	--	6	0	0	2	--	0	0	38	24	44	38	1.3	0	0.5	0	1.7	0	0.1	0
8/31/71	0.09 0 0.09	4.3	--	4.9	5.6	2	--	14	8					70	--	60	60	0.1	0	--	--	0.3	0	0.8	
10/1/71	2.81 0.46 3.27	4.9	4.6	5.0	5.4	--	4		0	6	--	16	0	38	24	38	38	0.1	0	0.1	0	0.1	0	0.1	0

TROUGH CREEK LIMESTONE BARRIER INSTALLATION AND EVALUATION
PROJECT NO. 14010-FWW
CR-105

SHEET II WATER ANALYSIS - SITE NO. 3

Sampling Date	Flow (cfs)	pH				Acidity (mg/l)				Alkalinity (mg/l)				SO_4 (mg/l)				Iron (mg/l)							
																		3-U		3-T		3B-D		3A-D	
		3-U	3-T	3B-D	3A-D	3-U	3-T	3B-D	3A-D	3-U	3-T	3B-D	3A-D	3-U	3-T	3B-D	3A-D	Total	Ferrous	Total	Ferrous	Total	Ferrous	Total	Ferrous
11/1/71	9.2 2.6 11.8	4.8	4.6	5.1	5.0	--	2	4	--	24	--	--	42	34	22	24	30	0.1	0	1.0	0	0.2	0	0.1	0
12/1/71	6.4 2.5 8.9	5.1	4.7	5.4	5.4	0	--	0	--	0	6	0	4	40	48	48	40	0.1	0	0.2	0	0.1	0	0.1	0
1/4/72	12.5 3.2 15.7	5.1	4.9	5.1	5.3	--	--	0	--	6	4	0	6	38	24	28	42	0.1	0	0.1	0	0.1	0	0.1	0
2/1/72	9.8 2.2 12.0	4.2	4.3	4.3	4.4	4	6	6	12	--	--	--	--	30	38	44	40	0.2	0	0.1	0	0.1	0	0.1	0
2/28/72	15.5 5.9 21.4	4.7	4.4	4.7	4.9	--	2	--	--	2	--	4	6	38	50	28	28	0.1	0	0.1	0	0.1	0	0.1	0
3/31/72	9.6 1.8 11.4	4.5	5.2	4.6	4.6	11	6	10	10	0	2	2	1	29	16	31	30	0.21	0.20	0.19	0.08	0.14	0.10	0.19	0.18
4/25/72	26.3 7.0 33.3	3.7	4.4	3.9	3.7	13	6	11	13	0	0	0	0	25	20	25	29	0.26	0.08	0.32	0.03	0.34	0.12	0.32	0.08
5/18/72	15.5 5.6 21.1	4.4	5.0	4.7	4.8	10	4	9	7	--	--	--	--	29	20	25	24	0.58	0.03	0.32	0.10	0.50	0.02	0.45	0.08
7/5/72	22.5 7.0 29.5	5.1	5.3	5.2	5.1	9	5	10	8	--	--	--	--	33	18	29	28	0.34	0.06	0.14	0.06	0.23	0.06	0.21	0.06
7/24/72	1.0 0.8 1.8	5.1	5.2	6.8	6.1	10	6	6	9	--	--	--	--	39	13	16	29.5	0.18	0.02	0.07	0.03	0.10	0.08	0.05	0.03
8/22/72	0.3 0.5 0.8	5.1	5.0	7.6	5.5	10	13	5	15	2	2	7	5	--	--	--	--	0.27	--	0.10	--	0.23	--	0.21	--
9/26/72	0.11 0.00 0.11	4.3		5.5	5.5	15		11	12	0		2	8	140		116	76	0.16	0.03			0.20	0.06	0.09	0.02

TROUGH CREEK LIMESTONE BARRIER INSTALLATION AND EVALUATION
PROJECT NO. 14010-FWW
CR-105

SHEET III WATER ANALYSIS – SITE NO. 3

Sampling Date	Flow (cfs)	pH				Acidity (mg/l)				Alkalinity (mg/l)				SO_4 (mg/l)				Iron (mg/l) 3-U		3-T		3B-D		3A-D	
		3-U	3-T	3B-D	3A-D	3-U	3-T	3B-D	3A-D	3-U	3-T	3B-D	3A-D	3-U	3-T	3B-D	3A-D	Total	Ferrous	Total	Ferrous	Total	Ferrous	Total	Ferrous
10/26/72	0.41 0.14 0.55	6.3	5.3	6.3	6.6	13	5	10	8	18	5	5	18	45	10.5	31.5	31	0.20	0.02	0.04	0.02	0.14	0.02	0.10	0.02
11/30/72	16.0 2.7 18.7	5.1	4.8	4.8	5.0	10	8	5	6	2	2	2	6	19.5	10.5	22.5	19.5	0.20	0.06	0.09	0.02	0.19	0.03	0.23	0.02
1/8/73	9.9 5.9 15.8	4.7	5.4	4.7	4.8	4	3	8	6	2	5	2	2	23	12	20.5	21	0.21	0.06	0.10	0.06	0.18	0.06	0.19	0.08
2/15/73	16.3 4.1 20.4	5.7	5.0	5.0	4.8	8	4	6	7	0	0	0	0	22	10	14	24	0.3	<0.2	<0.1	<0.1	<0.1	<0.1	0.2	<0.2
3/30/73	14.3 5.2 19.5	4.8	5.2	4.9	4.9	7	4	6	6	0	0	0	0	15	5	15	20	0.2	--	0.1	--	0.2	--	0.1	--
4/23/73	62.5 12.0 74.5	5.1	4.9	5.1	5.3	4	5	4	7	0	0	0	0	26	10	19	22	0.9	--	0.3	--	0.9	--	0.7	--
5/10/73	31.9 4.0 35.9	5.1	5.0	5.2	5.2	8	8	6	6	0	0	0	0	19	14	14	17	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
6/7/73	40.5 5.0 45.5	4.8	5.0	4.8	4.8	8	8	8	10	0	0	0	0	22	14	19	24	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
7/16/73	0.3 0.1 0.4	4.5	4.8	5.5	4.7	10	8	4	10	0	0	0	0	48	5	43	43	0.1	--	<0.1	--	0.1	--	0.1	--
8/17/73	0.2 Trickle 0.2	4.8	6.2	5.4	6.3	10	4	4	6	0	0	0	0	55	5	62	43	0.2	--	0.1	--	0.2	--	0.1	--
10/16/73	0.5 Trickle 0.5	4.8	5.6	6.2	6.8	4	4	4	0	0	0	0	0	62	5	55	46	0.1	--	<0.1	--	<0.1	--	<0.1	--
10/24/73	0.6 0.2 0.8	5.0	4.5	4.7	5.2	8	6	8	4	2	2	7	2	10	10	30	35	0	--	0	--	0	--	0.146	--
11/23/73	8.8 1.3 10.1	4.4	4.2	4.9	4.2	4	6	6	6	0	0	2	0	31	13	18	31	0.146	--	0	--	0	--	0	--

TROUGH CREEK LIMESTONE BARRIER INSTALLATION AND EVALUATION
PROJECT NO. 14010 - FWW
CR-105

SHEET IV WATER ANALYSIS - SITE NO. 3

Sampling Date	Flow (cfs)	pH				Acidity (mg/l)				Alkalinity (mg/l)				SO_4 (mg/l)				Iron (mg/l) 3-U		3-T		3B-D		3A-D	
		3-U	3-T	3B-D	3A-D	3-U	3-T	3B-D	3A-D	3-U	3-T	3B-D	3A-D	3-U	3-T	3B-D	3A-D	Total	Ferrous	Total	Ferrous	Total	Ferrous	Total	Ferrous
12/19/73	16.5	4.4				6				0				26				0.146	--						
	3.0		4.5				2				0				14					0.146	--				
	19.5			4.5	4.5			4	4			0	0			23	23					0.146	--	0.146	--
2/14/74	19.5	4.7				4				4				14				0.146	--						
	5.4		4.7				4				4				9					0.146	--				
	24.9			4.7	4.8			4	2			2	4			9	11					0.146	--	0.146	--
3/1/74	32	4.7				2				2				23				0	--						
	8		4.5				4				0				6					0	--				
	40			4.8	4.7			4	2			4	2			19	22					0	--	0	--
4/11/74	16.1	4.6				6				2				25				0	--						
	6.1		4.6				6				2				35					0	--				
	22.2			4.6	4.6			4	2			2	4			20	45					0	--	0	--
4/30/74	19.0	4.7				6				2				21				0	--						
	7.2		4.7				4				2				9					0	--				
	26.2			4.9	4.9			4	2			4	4			13	14					0	--	0	--
5/28/74	13.2	4.7				4				4				25				0	--						
	6.1		4.5				4				0				14					0	--				
	19.3			4.9	4.9			2	2			2	4			12	28					0	--	0	--
6/27/74	16.5	4.8				6				6				22				0	--						
	6.5		4.5				8				0				7					0	--				
	23.0			4.8	4.8			4	6			4	6			14	26					0	--	0	--
8/5/74	0.5	4.8				4				4				53				0	--						
	0.1		4.8				2				2				9					0.1	--				
	0.6			5.3	5.4			6	6			6	20			43	43					0	--	0	--

TROUGH CREEK LIMESTONE BARRIER INSTALLATION AND EVALUATION
PROJECT NO. 14010-FWW
CR-105

SHEET I. WATER ANALYSIS – SITE NO. 4

Sampling Date	Flow (cfs)	pH			Acidity (mg/l)			Alkalinity (mg/l)			SO_4 (mg/l)			Iron (mg/l) 4-U		4-T		4-D	
		4-U	4-T	4-D	4-U	4-T	4-D	4-U	4-T	4-D	4-U	4-T	4-D	Total	Ferrous	Total	Ferrous	Total	Ferrous
10/2/70	1.2*	4.6			10			0			56			0.67					
	0.3*		6.7			0			12			36				0.6			
10/28/70	5.0*	5.0			4			4			--			0.1					
11/27/70	N.R.	4.7			2			0			--			0.35					
12/30/70	N.R.	4.6			6			0			22			0.3					
2/26/71	N.R.	5.5			0			0			24			0.3	0				
3/30/71	N.R.	4.9			16			--			36			0.1	0				
4/28/71	N.R.	5.0			4			0			28			0.4	0				
5/28/71	N.R.	4.6			0			0			22			0.1	0				
	N.R.		6.5			--			14			24				0.3	0		
7/2/71	0.78	4.6			2			--			28			0.1	0				
	0.47		6.8			--			28			24				0.7	0		
8/5/71	3.85	6.2			0			0			44			1.3	0				
	0.68		7.0			--			20			30				0.5	0		
	4.53			6.5			--			12			30					4.4	0
8/31/71	0.08	6.8			--			14			22			0.3	0				
	0.03		6.8			--			36			22				0.5	0		
	0.11			8.7			--			18			30					0.1	0
10/1/71	3.68	5.6			0			0			38			0.1	0				
	0.36		6.7			--			40			48				0.1	0		
	4.04			6.4			--			12			38					0.1	0
11/1/71	18.6	6.3			--			10			30			0.4	0				
	1.8		6.3			--			80			38				0.5	0		
	20.4			5.7			--			20			22					0.3	0
12/1/71	16.8	5.3			--			6			38			0.1	0				
	1.5		6.4			--			18			24				0.2	0		
	18.3			5.9			--			18			30					0.1	0
1/4/72	19.4	5.3			--			4			30			0.1	0				
	2.0		6.7			--			16			28				1.0	0		
	21.4			6.1			--			40			40					0.1	0
2/1/72	13.8	4.4			4			--			48			0.1	0				
	2.0		5.9			--			10			42				0.3	0		
	15.8			5.0			0			0			54					0.1	0

TROUGH CREEK LIMESTONE BARRIER INSTALLATION AND EVALUATION
PROJECT NO. 14010-FWW
CR-105

SHEET II WATER ANALYSIS - SITE NO. 4

Sampling Date	Flow (cfs)	pH			Acidity (mg/l)			Alkalinity (mg/l)			SO_4 (mg/l)			Iron (mg/l)					
														4-U		4-T		4-D	
		4-U	4-T	4-D	4-U	4-T	4-D	4-U	4-T	4-D	4-U	4-T	4-D	Total	Ferrous	Total	Ferrous	Total	Ferrous
2/28/72	39.1 5.1 44.2	4.9	6.2	5.6	--	--	--	24	58	32	30	24	24	0.1	0	0.1	0	0.1	0
3/31/72	12.0 1.7 13.7	4.7	7.1	5.1	0.9	4	7	1.0	12	1	27	20	30	0.19	0.1	0.52	0.12	0.09	0.03
4/25/72	48.5 6.5 55.0	4.0	6.2	4.5	11	8	9	0	7	0	21	26	23	0.33	0.03	0.26	0.06	0.24	0.08
5/18/72	22.6 3.2 25.8	4.7	5.0	5.7	--	--	--	1	3	6	17	21	20	0.30	0.06	0.27	0.12	0.52	0.10
7/5/72	39.4 10.6 50.0	5.6	7.1	6.5	7	7	7	--	--	--	28	18	26	0.14	0.03	0.32	0.02	0.23	0.03
7/24/72	2.9 0.7 3.6	7.3	5.9	6.5	5	10	4	--	--	--	11.5	23.5	19.3	0.41	0.03	0.14	0.10	0.20	0.06
8/22/72	0.5 0.5 1.0	7.3	6.0	7.4	5	9	5	8	25	18	--	--	--	0.12	--	0.59	--	0.27	--
9/26/72	0.16 0.07 0.23	5.9	6.0	7.1	32	16	8	11	27	33	31	11.5	23	0.16	0.06	0.72	0.10	0.23	0.10
10/26/72	0.57 0.45 1.02	6.8	6.9	6.8	4	0	0	5	20	10	26	12.5	22	0.10	0.02	0.54	0.03	0.20	0.03
11/30/72	37.2 5.7 42.9	4.9	7.4	7.1	6	0	5	2	17	8	16.5	8	14	0.18	0.03	0.23	0.02	0.12	0.03
1/8/73	20.0 2.5 22.5	5.5	6.5	5.9	4	0	0	5	12	9	19.3	12.5	18	0.09	0.06	0.03	0.10	0.19	0.10
2/15/73	28.1 5.7 33.8	4.8	6.6	5.6	9	0	3	0	1	0	17	2	17	0.1	<0.1	0.4	<0.2	0.2	<0.2

TROUGH CREEK LIMESTONE BARRIER INSTALLATION AND EVALUATION
PROJECT NO. 14010-FWW
CR-105

SHEET III WATER ANALYSIS - SITE NO. 4

Sampling Date	Flow (cfs)	pH			Acidity (mg/l)			Alkalinity (mg/l)			SO_4 (mg/l)			Iron (mg/l) 4-U		4-T		4-D	
		4-U	4-T	4-D	4-U	4-T	4-D	4-U	4-T	4-D	4-U	4-T	4-D	Total	Ferrous	Total	Ferrous	Total	Ferrous
3/30/73	23.0 2.8 25.8	5.0	6.8	6.6	6	0	1	0	6	0	20	3	10	0.1	--	0.4	--	0.2	--
4/23/73	88.8 10.2 99.0	5.6	6.3	6.0	3	0	2	0	2	0	26	10	12	6.4	--	15	--	6.5	--
5/10/73	42.2 2.5 44.7	5.6	6.7	6.0	4	0	4	0	10	0	19	5	12	<0.1	<0.1	0.2	<0.2	<0.1	<0.1
6/7/73	80.7 3.3 84.0	5.0	6.8	6.0	8	0	6	0	6	0	19	10	19	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
7/16/73	1.6 0.2 1.8	6.4	6.5	6.2	C	0	0	4	10	2	14	2	19	0.1	--	<0.1	--	0.1	--
8/17/73	0.2 0.1 0.3	6.9	6.8	6.6	0	0	0	18	24	16	5	5	22	0.2	--	0.2	--	0.2	--
10/16/73	0.6 0.1 0.7	6.3	6.9	6.8	0	0	0	12	26	26	14	2	22	<0.1	--	0.2	--	<0.1	--
10/24/73	0.6 0.1 0.7	5.1	6.1	5.9	4	6	4	4	20	6	35	25	30	0.146	--	0.146	--	0	--
11/23/73	9.0 1.1 10.1	4.4	5.6	5.2	6	2	6	0	4	2	27	11	21	0	--	0.146	--	0	--
12/19/73	35.0 6.0 41.0	4.7	5.6	5.2	2	4	2	2	8	2	20	14	17	0	--	0	--	0	--
2/14/74	31.5 3.3 34.8	5.2	5.8	5.3	4	2	4	6	14	6	14	13	14	0.146	--	0.439	--	0	--
3/1/74	44.0 6.0 50.0	5.1	5.6	5.5	2	4	4	6	14	8	18	17	16	0	--	0	--	0	--

TROUGH CREEK LIMESTONE BARRIER INSTALLATION AND EVALUATION

PROJECT NO. 14010-FWW

CR-105

SHEET IV WATER ANALYSIS - SITE NO. 4

Sampling Date	Flow (cfs)	pH			Acidity (mg/l)			Alkalinity (mg/l)			SO_4 (mg/l)			Iron (mg/l) 4-U		Iron (mg/l) 4-T		Iron (mg/l) 4-D	
		4-U	4-T	4-D	4-U	4-T	4-D	4-U	4-T	4-D	4-U	4-T	4-D	Total	Ferrous	Total	Ferrous	Total	Ferrous
4/11/74	20.8	5.8			2			6			30			0	--				
	3.2		5.8			4			20			30				0	--		
	24.0			5.5			2			6			40					0	--
4/30/74	26.2	5.7			4			6			17			0	--				
	3.8		6.0			4			24			6				0	--		
	30.0			5.6			6			10			16					0	--
5/28/74	20.5	5.7			2			10			18			0	--				
	2.5		5.5			2			22			8				0	--		
	23.0			5.1			4			6			19					0	--
6/27/74	25.0	5.4			4			6			17			0	--				
	3.0		5.2			8			20			8				0.4	--		
	28.0			5.0			4			10			12					0	--
8/5/74	0.8	6.1			4			20			16			0	--				
	0.1		6.3			4			22			9				0.1	--		
	0.9			5.9			8			16			24					0	--

TROUGH CREEK LIMESTONE BARRIER INSTALLATION AND EVALUATION
PROJECT NO. 14010 - FWW
CR-105

SHEET I WATER ANALYSIS - SITE NO. 5

Sampling Date	Flow (cfs)	pH		Acidity (mg/l)		Alkalinity (mg/l)		SO_4 (mg/l)		Iron (mg/l)			
		S-U	S-D	S-U	S-D	S-U	S-D	S-U	S-D	S-U Total	S-U Ferrous	S-D Total	S-D Ferrous
10/2/70	0.2#	3.1		600		0		750		14			
12/30/70	N.R.	2.9		180		0		400		37.5			
4/28/71	N.R.	3.0		200		0		350		20	8		
5/28/71	0.2		5.7		--		6		310			0.45	0
7/2/71	0.2		5.5		0		0		320			0.4	0
8/5/71	0.15		6.2		--		24		310			1.8	0
8/31/71	0.12		4.3		64		--		270			2.9	0
10/1/71	0.28		3.4		96		--		320			2.8	0.3
11/1/71	0.2		3.4		108		--		320			15.5	1.3
12/1/71	0.3		3.6		80		--		220			3.8	0.2
1/4/72	0.4		3.1		54		--		425			2	0.1
2/1/72	0.4		2.5		130		--		300			2.9	0.6
2/28/72	Site not accessible - Snow												
3/31/72	0.5		3.0		151		0		210			2.88	0.98
4/25/72	0.96		3.6		97		0		310			4.80	0.20
5/18/72	1.0		3.6		74		--		246			2.30	0.27
7/5/72	1.15		4.2		97		--		246			3.84	0.12
7/24/72	0.5		3.5		93		--		208			3.96	0.12
8/22/72	0.6		4.2		95		0		--			676	--

(Con't) SHEET II WATER ANALYSIS - SITE NO. 5

TROUGH CREEK LIMESTONE BARRIER INSTALLATION AND EVALUATION
PROJECT NO. 14010 - FWW
CR-105

Sampling Date	Flow (cfs)	pH		Acidity (mg/l)		Alkalinity (mg/l)		SO_4 (mg/l)		Iron (mg/l)			
		S-U	S-D	S-U	S-D	S-U	S-D	S-U	S-D	S-U		S-D	
										Total	Ferrous	Total	Ferrous
9/26/72	0.2	3.8		79		--		290				13.0	0.24
10/26/72	0.16	3.9		70		30		220				22.0	0.18
11/30/72	0.53	3.3		190		--		220				10.6	0.22
1/8/73	0.30	3.0		140		--		180				3.6	0.24
2/15/73	Samples Not Collected - Site Not Accessible												

TROUGH CREEK LIMESTONE BARRIER INSTALLATION AND EVALUATION
PROJECT NO. 14010 - FWW
CR-105

SHEET I WATER ANALYSIS - SITE NO. 6

Sampling Date	Flow (cfs)	pH		Acidity (mg/l)		Alkalinity (mg/l)		SO_4 (mg/l)		Iron (mg/l)			
		6-U	6-D	6-U	6-D	6-U	6-D	6-U	6-D	6-U Total	6-U Ferrous	6-D Total	6-D Ferrous
10/2/70	2.5*	4.7		14				58		0.1			
10/28/70	N.R.	4.9		4		6		--		0.1			
11/27/70	N.R.	4.7		2		0		--		0.5			
12/30/70	N.R.	4.3		6		0		28		1.9			
1/26/71	N.R.	4.6		0		0		24		1.1			
2/26/71	N.R.	4.8		2		0		28		0.65	0		
5/28/71	N.R.	5.7		--		4		32		0.4	0		
7/2/71	N.R.	6.4		--		6		40		0.8	0		
8/5/71	N.R.	6.3		--		6		42		0.4	0		
8/31/71	1.05	6.1		6		--		95		0.7	0		
10/1/71	6.65	5.5		0		0		40		0.1	0		
11/1/71	N.R.	5.8		--		10		22		1.0	0		
12/1/71	50.3	5.9	6.0	--	--	18	10	40	24	0.3	0	0.5	0
1/4/72	33.3	6.0	6.0	--	--	4	6	22	24	0.1	0	0.1	0
2/1/72	17.3	5.0	5.2	2	--	--	8	40	28	0.1	0	0.3	0
2/28/72	71.0	5.3	5.4	--	--	14	20	38	44	0.1	0	0.1	0
3/31/72	18.3	4.9	5.0	7	14	1	2	23	31	0.24	0.1	0.19	0.18
4/25/72	65.0	4.6	4.6	7	8	1	1	23	25	0.29	0.03	0.21	0.02
5/18/72	34.0	5.7	6.4	4	2	--	--	21	16	0.69	0.65	0.41	0.12

TROUGH CREEK LIMESTONE BARRIER INSTALLATION AND EVALUATION
PROJECT NO. 14010 - FWW
CR-105

(Con't) SHEET II WATER ANALYSIS - SITE NO. 1

Sampling Date	Flow (cfs)	pH		Acidity (mg/l)		Alkalinity (mg/l)		SO_4 (mg/l)		Iron (mg/l)			
										6-U		6-D	
		6-U	6-D	6-U	6-D	6-U	6-D	6-U	6-D	Total	Ferrous	Total	Ferrous
7/5/72	108	5.7	6.2	6	7	--	--	30	27	0.63	0.03	0.50	0.03
7/24/72	5.3	6.6	6.8	6	7	--	--	25.5	27	0.29	0.03	0.33	0.06
8/22/72	2.0	6.0	7.5	13	7	7	11	--	--	0.23	--	0.29	--
9/26/72	0.5	5.7	6.8	23	8	7	17	48	54	0.41	0.12	0.36	0.10
10/26/72	2.1	6.0	6.2	4	1	6	13	25.5	25.5	0.44	0.02	1.06	0.06
11/30/72	62.5	5.0	4.7	5	4	5	1	16	16.5	0.29	0.02	0.29	0.02
1/8/73	45.0	5.5	5.7	10	4	2	4	19	20	0.29	0.10	0.33	0.10
2/15/73	51.6	5.2	5.2	7	4	0	0	17	14	0.3	<0.2	0.3	<0.2
3/30/73	35.5	5.7	6.4	4	2	0	0	12	12	0.2	- --	0.2	- --
4/23/73	206	5.5	5.5	2	6	0	0	17	17	0.5	- --	1.2	- --
5/10/73	62.0	5.9	5.9	6	4	0	0	14	17	0.2	0.2	<0.2	<0.2
6/7/73	95	5.5	5.4	14	4	0	0	24	22	0.1	<0.1	<0.1	<0.1
7/16/73	2.8	5.9	6.1	4	0	0	0	29	38	<0.1	- --	<0.1	- --
8/17/73	0.5	6.4	6.8	2	0	0	0	24	38	0.2	- --	0.3	- --
10/16/73	2.3	5.3	5.9	4	2	0	0	72	67	0.1	- --	<0.1	- --
10/24/73	1.5	5.4	5.1	8	6	4	4	45	40	0	- --	0	- --
11/23/73	11.5	5.1	5.1	8	4	2	2	27	29	0	- --	0.146	- --
12/19/73	65.0	4.8	4.9	4	2	2	2	23	18	0.146	- --	0.146	- --

(Con't) SHEET III WATER ANALYSIS - SITE NO. 6

Sampling Date	Flow (cfs)	pH		Acidity (mg/l)		Alkalinity (mg/l)		SO_4 (mg/l)		Iron (mg/l)			
		6-U	6-D	6-U	6-D	6-U	6-D	6-U	6-D	6-U		6-D	
										Total	Ferrous	Total	Ferrous
2/14/74	45.5	5.2	5.2	2	4	4	4	16	14	0.146	- --	0	- --
3/1/74	65	5.4	5.4	2	2	4	6	17	17	0	- --	0	- --
4/11/74	33	5.5	5.6	4	4	4	6	35	30	0	- --	0	- --
4/30/74	38	5.5	5.6	4	4	6	4	22	26	0	- --	0	- --
5/28/74	46	5.4	5.6	4	2	4	6	23	25	0	- --	0	- --
6/27/74	40	5.3	5.3	4	8	4	4	23	27	0	- --	0	- --
8/5/74	1.3	5.0	5.8	4	6	4	10	43	43	0	- --	0.2	- --